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13. ABSTRACT *(Maximum 200 words)*

This annual report covers the period from June 1997 through September 1998. The Field Emission X-ray Sensor (FEXIS) is a novel flat panel combination of the X-ray photoconductor thallium bromide and a field emitter array readout. The objective of this program was to develop and implement proof-of-concept FEXIS design of a mammography sensor. The second objective was to investigate structure modifications that would lead to a viable production mammography sensor. The FEXIS concept was analyzed in detail and a prototype design was developed. A prototype FEXIS was built, but tests were incomplete. The field emitter panel supplier, FED, Inc., was unable to panels on time so the experimental program is behind schedule. The analytical program was carried out to the extent possible in the absence of experimental results. The results so far indicate that the FEXIS mammography sensor is feasible, but that the enabling field emitter array technology is not yet well enough advanced to be applicable. However, small proof-of-concept FEXIS devices meeting the program objectives can be made and tested. Due to continued array delivery problems, an alternative flat panel imaging concept that will allow all of the program objectives to be met may be proposed.

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Annual Progress Report
Grant No. DAMD17-97-1-7016

A Novel High Resolution, Low Dose Flat Panel
Mammography Detector Technology

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1. Introduction

Overview

This annual progress report describes work carried out in the first 15 months of a two year mammography sensor development program. Due to delays in procuring field emission arrays, a component vital to the program, a three month no-cost extension was requested and granted. At this time, continued delivery delays have caused the experimental program to stagnate. In spite of these delays, much of the analytical task has been carried out. A new field emission array is expected in October and it is anticipated that the experimental program can then be resumed. Also, an alternative approach that would lead to the completion of program objectives is being considered and may be proposed to the contracting agency in October. There is a significant portion of the original program funding still available to consider an alternative option.

Reporting Period and Format

This annual report covers activities undertaken between June 1, 1997 and September 30, 1998. The report is organized around the specific objectives as presented in the original Statement of Work. Appendices that provide additional detail are provided. Objectives 1, 2 and 3 are addressed. Objective 4 tasks remain to be done.

Technology Review

The X-ray imaging photoconductor thallium bromide, has been under development by Xicon Technologies, working in collaboration with the University of Connecticut Health Center (UCHC), since 1993. In 1996, the feasibility of using thallium bromide (TlBr) as a high performance X-ray imaging medium was clearly demonstrated by the successful implementation of the **X**-ray Sensitive **E**lectron **B**eam **I**mage **T**ube (XEBIT) that employed conventional cathode ray tube electron beam readout techniques. Both one inch and nine inch field of view (FOV) XEBIT devices were evaluated and resolution of over 10 line pairs per millimeter (lp/mm) and a detective quantum efficiency (DQE) in excess of over 60% at 59 keV X-ray energy were demonstrated.

Program Mission

The hypothesis to be proven in this program is that the XEBIT electron beam source can be replaced with an addressable array of cold cathode field emitters in a novel **F**ield **E**mission **X**-ray **I**maging **S**ystem (FEXIS) specifically optimized for mammography. This new flat panel sensor would for the first time combine the high resolution and sensitivity of a thallium bromide X-ray photoconductor, with the high resolution inherent in a dense array of field emitter cold cathodes, providing a mammography imaging system with unprecedented performance. Thus, the analysis, design and fabrication efforts undertaken through this grant were focused on the replacement of the bulky scanning cathode ray tube electron beam source with the flat panel addressable field emission array and the evaluation of FEXIS structures both experimentally and analytically.

In order to understand the issues involved in making this transition, it is useful to review the XEBIT operation.

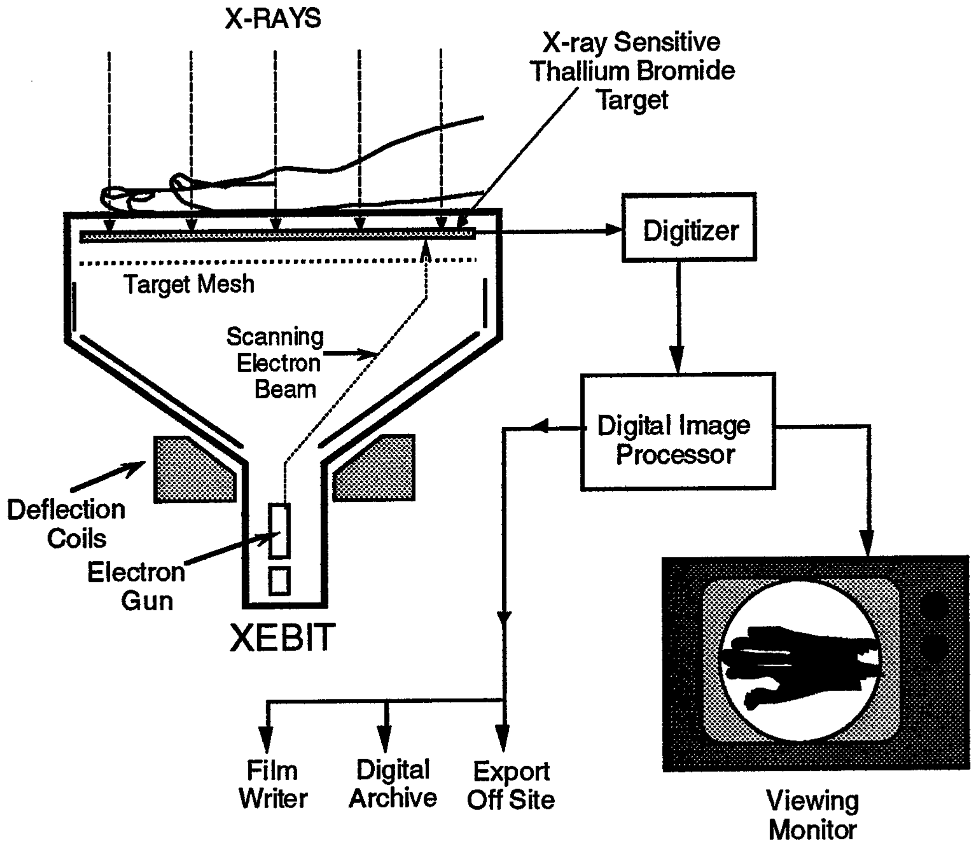


Figure 1. Simplified XEBIT system illustration with key components.

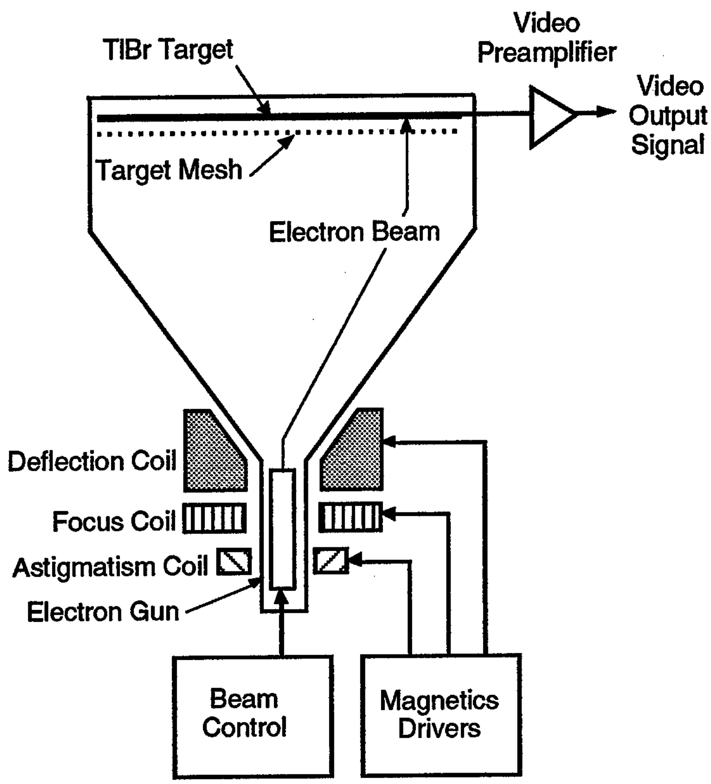
The simplified XEBIT illustrated in Figure 1 employs a target consisting of an X-ray transparent signal plate and a photoconductive TlBr layer between 50 and 350 microns thick depending on the X-ray energy range of interest. The electron beam required for readout is generated by the electron gun in the neck of the tube. A precision magnetic deflection system causes the electron beam to scan the target in a raster pattern during readout. Dynamic magnetic focus and astigmatism correction algorithms ensure a uniform electron beam spot size comparable to that of a resolution element over the entire imaging area. The XEBIT is positioned where a film screen or image intensifier would be typically placed and X-ray images are acquired in a three step sequence.

1) The scanning electron beam, accelerated by appropriate electric fields, passes through the field mesh and uniformly pre-charges the entire backside of the TlBr target to ground potential in 30 milliseconds. The front side of the target (signal Plate) is uniformly biased to a positive potential, typically 200 volts, so an electric field is created across the TlBr layer. The field mesh collects any excess electrons that are repelled by the target after it has been charged to ground potential.

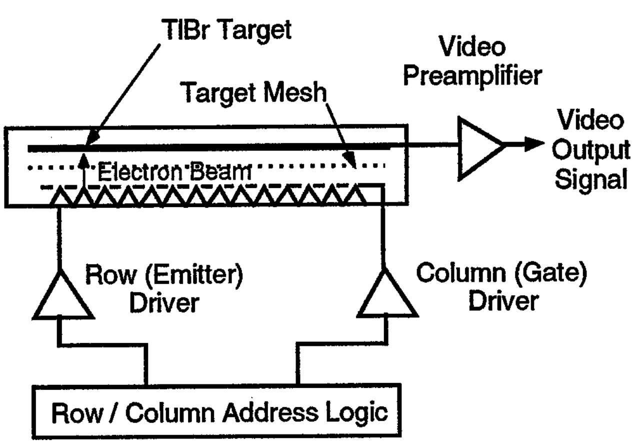
2) The X-ray exposure is then made. During the exposure, X-rays generate electrical charge in the TlBr layer that locally discharges the scanned surface in a spatial pattern corresponding to that of the impinging X-rays.

3) The electron beam again scans and re-charges the target generating a video signal in response to the regions that were discharged during the exposure. In highlights, the positive potential that the beam must re-charge can be quite high and the target surface can go into a secondary emission mode, thus preventing highlight discharge. This problem has been solved in vidicons by applying an anti-secondary emission coating. In the XEBIT, a composite coating of crystalline and porous antimony sulfide has been applied over the TlBr to successfully minimize secondary emission.

The XEBIT may be sequenced through steps 1 - 3 in a continuous fashion up to 60 frames per second for video fluoroscopy or be operated in a snapshot mode for acquiring diagnostic quality still images. Both resolution and field size are programmable providing the ability to acquire regions of interest or full field images. The analog signal may be used directly or be digitized to 4096 intensity levels (12 bits) for input to digital image management systems. Figure 2 illustrates how the XEBIT electron gun and associated magnetics would be replaced with an addressable cold cathode field emission panel in the proposed FEXIS configuration.



XEBIT X-ray Imaging system



FEXIS X-ray Imaging system

Figure 2. The evolution of the XEBIT to a flat panel FEXIS configuration.

The report body is organized around the specific objectives as presented in the original Statement of Work.

Objective 1.

Demonstrate the feasibility of a high performance flat panel imaging detector based on the combination of a thallium bromide photoconductor and field emission readout.

Two programs were implemented to meet this objective. The first was an analytical program in which proof-of-concept FEXIS specifications were developed using the current field emitter and XEBIT knowledge base. A FEXIS design was generated that employed available emitter array technology. The second program focused on implementation of the designs and evaluation of actual FEXIS devices.

The Field Emitter Array

The field emitter electron source that is proposed to replace the conventional cathode ray tube is a new technology being developed by the display industry. In a field emitter display, an addressable array of micro-tips selectively emit electrons through field assisted emission. An array of gates, located close to the tips, initiate and control electron emission. The **F**ield **E**mitter **D**isplay (FED) employs a phosphor screen to display images in a manner similar to that of a CRT. The emitter tips can be "turned on" by activating selected gates in a prescribed pattern to create a scanning electron beam raster. The FED produces images of high brightness and clarity that can be viewed over a wide solid angle. Each pixel consists of several hundred to several thousand emitter tips so that a few dead tips do not significantly degrade performance.

A pixel is activated when a tip grouping is switched from an intermediate positive potential to ground and the corresponding gates are switched from ground to a positive potential that is high enough to stimulate tip emission. The display is configured in a matrix with column address lines that are connected to tips and orthogonal row address lines that are connected to gates. Electron emission can be made to occur at multiple pixel sites by switching the voltages supplying the tip and gate address lines in parallel. This feature is exploited in a novel segmented target FEXIS design that is discussed further on in the report. Typically, tips are switched from about +40 volts to ground while gates are switched from 0 volts to +80 volts. Thus, at the intersection of selected tip and gate lines, the 80 volt field initiates and sustains electron emission.

When a row is switched to 80 volts, the tips that are not selected (de-selected) remain at the quiescent 40 volt level. This assumes that no emission will occur when the gates are switched to 80 volts, and a gate-to-emitter potential of only 40 volts exists at de-selected tips. Typically, emission is initiated when the gate-to-emitter potential exceeds 55 to 60 volts. When the upper tip voltage level is properly set, there should be no emission from de-selected tips, but threshold variations within an array may not allow this condition to be wholly achieved.

Figure 2 illustrates the relationship between the XEBIT and the FEXIS approach to the design of the X-ray imager. In both cases, the TlBr photoconductor is read out by a scanning electron beam. During the XEBIT development, an extensive analysis of the

electron optics and TlBr behavior as an X-ray photoconductor were carried out. Several beam current parameters were determined through computer simulations and subsequently verified with operational XEBITs. An important task in the FEXIS development was the characterization of the field emitter array in the context of imaging device requirements which differ from those of a display. Suggested reading at this point is Appendix B, A survey of Field Emitter Arrays that was prepared for this program by Dr. Cha-Mei Tang.

FEXIS Electron Beam Requirements

Electron beam current, as opposed to electronic charge, is used in the following discussion. The charging of the target by an electron beam is a complex process that is beam-geometry, scanning-speed, field-size and image-content dependent. The beam current data presented herein were obtained with a nine inch XEBIT operating at 30 frames per second (30FPS) in full field mode. During this evaluation, it was found that the beam current necessary to re-charge the target to ground potential was four times higher than the charge in an image. In addition, half of the available beam current was absorbed by the field mesh. This reserve beam, discovered in the early days of vidicon development[3], is necessary because of losses due to secondary emission and the fact that only the leading edge of the scanning beam contributes to target re-charge.

The need for such a high beam current placed a difficult requirement on the XEBIT electron gun. Typically, cathode ray display tubes operate at a few microamperes and rely on high accelerating potentials to create bright displays on a phosphor screen. In the XEBIT imager, under radiographic X-ray levels, highlights may require a beam current of 30 microamperes. Because of the known re-charge inefficiency and the beam loss due to mesh absorption, the XEBIT electron gun was specified to provide up to 160 microamperes of beam current. This difficult goal was ultimately met through a novel electron gun design and by optimizing the gun geometry. Based on XEBIT development work, the high beam current requirement was a major concern for the FEXIS program.

In both the XEBIT and FEXIS, electrons are accelerated axially through the field mesh and then decelerated toward the target landing at near zero velocity, hence, radial trajectory components are of concern. The XEBIT electron optics were developed with computer simulations that constrained the beam to approach the mesh and target normal to the target surface. This was accomplished by the introduction of a collimating electrode that essentially reversed the radial trajectory component, imposed by the deflection system. It was determined in XEBIT simulations, and later by experience, that a variance from the normal of ± 2 degrees would be an acceptable deviation in a nine inch device. This was achieved using only a static DC potential on the collimation electrode. Further studies showed that essentially perfect collimation could be achieved by dynamically controlling the collimation electrode potential, a difficult, but not impossible option. The result of imperfect beam landing is loss of dynamic range and a spatial variation in the potential to which the target is charged during readout.

The XEBIT cathode operates ostensibly at ground potential and the target is biased to some positive potential above ground. In the field emitter array, the tip operates at a

few volts positive with respect to ground due to the integrated emission stabilization resistance. Thus, the scanning electron beam charges the target backside to a potential that is a few volts above ground potential. In the FEXIS, it was necessary to set the target bias voltage more positive than the tip potential to produce the required electric field across the photoconductor target.

While collimation and beam spot size parameters are uncoupled in the XEBIT, this is not the case in the FEXIS. There are no deflection fields in the FEXIS and collimation deviation arises due to tip emission patterns at each pixel. Low velocity beam landing was of concern in the FEXIS since electrons emitted by the cold cathode tips are typically not well collimated and beam spot size could be compromised resulting in a loss of resolution. A series of computer tip emission trajectory simulations were carried out to determine how the field emitter would behave in the FEXIS configuration. The results showed that current emitter technology could not provide the beam spot size necessary for a mammography FEXIS. The simulation report and data are provided in Appendix A.

In the XEBIT, frame rates of 60 per second are readily achieved using conventional display tube magnetics. In the FEXIS, this frame rate presents a potential problem since a FED emitter panel operates in a line mode, analogous to a line printer, where an entire row of emitters are active for a line time, typically 50 microseconds or more. Due to high array capacitance and finite array driver current, FED addressing speed is typically limited to 400 kHz. At this pixel frequency it would take 62.5 seconds to read out a 5000 x 5000 pixel image, clearly an unacceptable situation. The requirement of addressing the FEXIS pixel by pixel at 10 MHz or higher frequencies would require a parallel readout scheme that capitalized on the emitter multiplex advantage offered by FED technology.

Thus, during the FEXIS analysis and design phase, **beam current, beam collimation** and **scanning speed** were areas that required special attention. Based on XEBIT data, studies by electron optics consultants and input from FED, Inc., technical staff, a flat panel field emitter specification was developed for a prototype FEXIS radiographic sensor.

Prototype FEXIS Specification

General Architecture

The purpose of making the prototype sensor is to validate the FEXIS concept. The prototype is a two dimensional imaging sensor based on an addressable cold cathode electron emitter array in conjunction with a TlBr X-ray sensitive photoconductor. Matrix addressing, in which each row and column are sequentially activated, is required. A nickel field mesh electrode is required between the flat panel emitter structure and the photoconductor. The entire assembly will be contained in a vacuum housing which will be continuously pumped to a pressure of 10^{-7} to 10^{-8} Torr. A production FEXIS would be sealed-off and employ a suitable getter to maintain vacuum integrity.

Emitter Panel Design Specifications

Two device types will be built in this prototype development program. The first is a visible imager (FES) with relaxed beam and resolution requirements to facilitate imager concept evaluation. The second is an X-ray imager requiring higher resolution and higher beam currents that will be evaluated at X-ray levels commonly used for general radiography. This two tiered approach is reflected in the specifications below.

Beam Current per Pixel	
Visible Device (FES)	1 Microampere
X-ray Device (FEXIS)	120+ Microamperes
Beam Current Tolerance	+50% -10% The FEXIS is relatively insensitive to beam current variations across the field of view. Once the target is fully charged, excess beam current is reflected back to the field mesh.
Beam Collimation	Beam collimation is of importance in a FEXIS. Electrons emitted by the FE tips must follow a trajectory such that they approach the target normal to the target surface within a specified spot size that is comparable to the pixel dimension.
Beam Collimation Tolerance	$\pm$ 2 Angular degrees at the target mesh.
Pixel Size	
Visible Device	Consistent with available FED panels.
First X-ray Device	Nominally 100 x 100 Microns
Product Goal	50 x 50 Microns
Image Format	
Initial and Interim Devices	Consistent with available panels but, nominally 2" x 2".
Product Goal	10" x 10"

Addressing Modes	Full Sequential, Pixel by Pixel. Unlike a FED, both rows and columns must be sequentially addressed. Modified FED drivers and logic will be required for the FEXIS.
Pixel Addressing Speed	
Initial Devices	Consistent with available structures.
Final Goal	20 MHz The FEXIS can be implemented in a multiple target configuration where as many as 32 pixels are addressed in parallel at <u>0.63 MHz</u> to achieve an equivalent 20 MHz readout speed.

Timing Requirements

The required row (gate) column (emitter) address timing is given in Figure 3. Row and column functions may be transposed. A pixel emitter is turned on by lowering the emitter voltage to 0 volts and raising the gate voltage to +80 volts. Field emission occurs only at the intersection of the addressed row and column with all other pixels presumably in a fully "off" state.

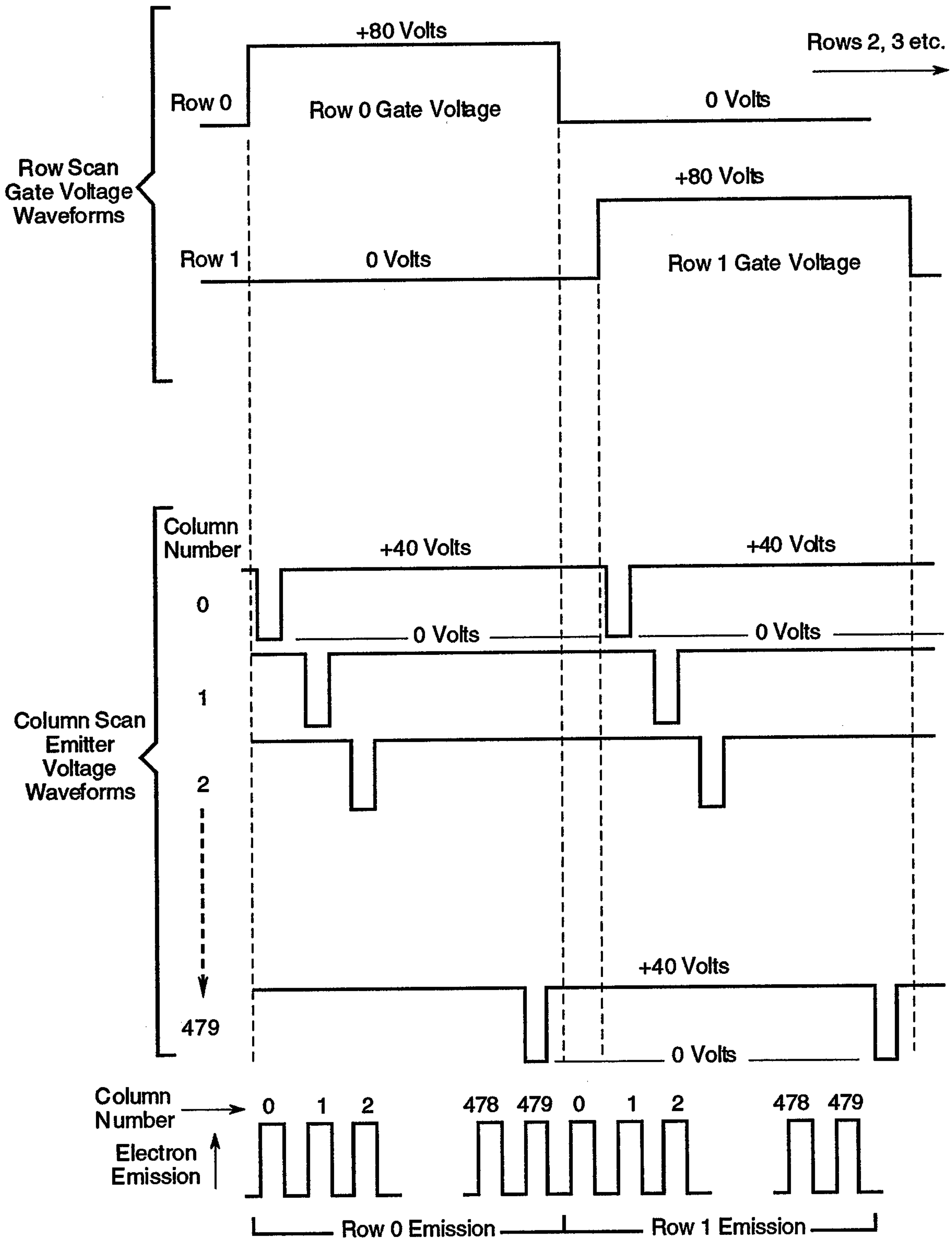


Figure 3. Timing requirements for the FEXIS flat panel imager.

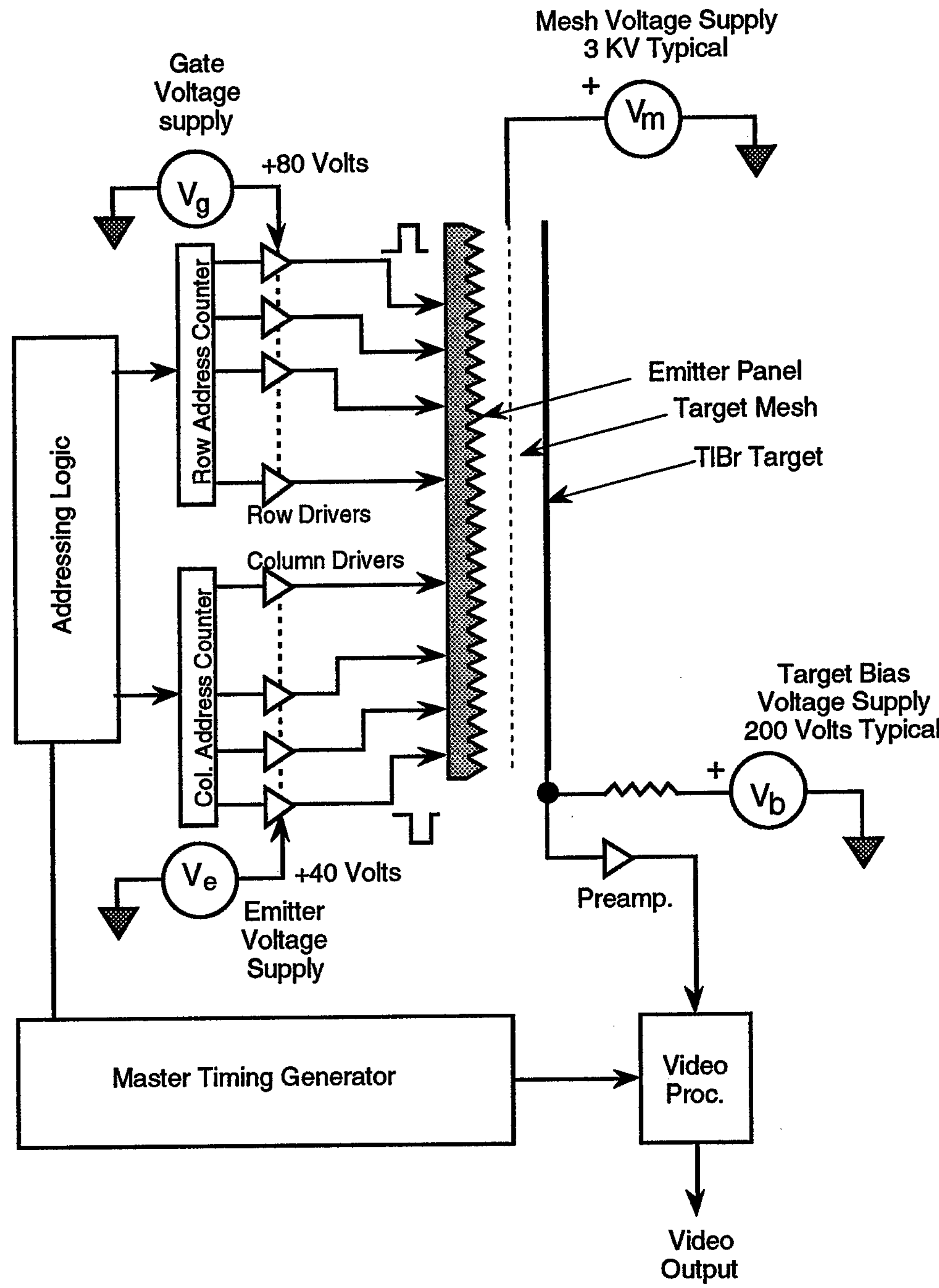


Figure 4. FEXIS system block diagram.

The FEXIS support electronics illustrated in Figure 4 are conceptually simple. The emitter panel selected for the prototype unit was a 480 x 480 pixel device with 110 micron square pixels. The panel is powered by row and column drivers connected to digital counters that sequence through the array as illustrated in Figure 3. The addressing logic sequentially generates 480 individual signals for the rows and columns respectively. The row and column drivers are connected to the array through six printed circuit ribbons (Flex Circuits) that are bonded with a cold pressure forming technique. The mesh and bias voltages are provided by high quality adjustable laboratory power supplies. The low noise preamplifier and video processor were adapted from an existing vidicon camera system design.

Prototype Implementation

The FEXIS specification was delivered to FED, Inc., the contractor selected to supply the emitter panels and driver electronics, in August 1997. During the following six months, FED, Inc. developed the emitter panel and driver electronics and Xicon Technologies assembled and tested the mechanical, vacuum and electrical components. An emitter array sample was obtained and the demountable mechanical vacuum housing that would allow emitter arrays to be attached was designed and built. The FEXIS mechanical design is illustrated in Figure 5. All internal components were vacuum compatible and the device could be disassembled to facilitate the introduction of different targets. Target and mesh spacing could be readily changed as required. Two assemblies were made so that when one was being modified, the other could be attached to the array and maintained under vacuum.

One major consideration was the known degradation of an emitter array when exposed for prolonged periods (1 hour) to air. With the imager design illustrated in Figure 5, the air exposure time was reduced to less than a minute during the integration of the array and the vacuum housing assembly.

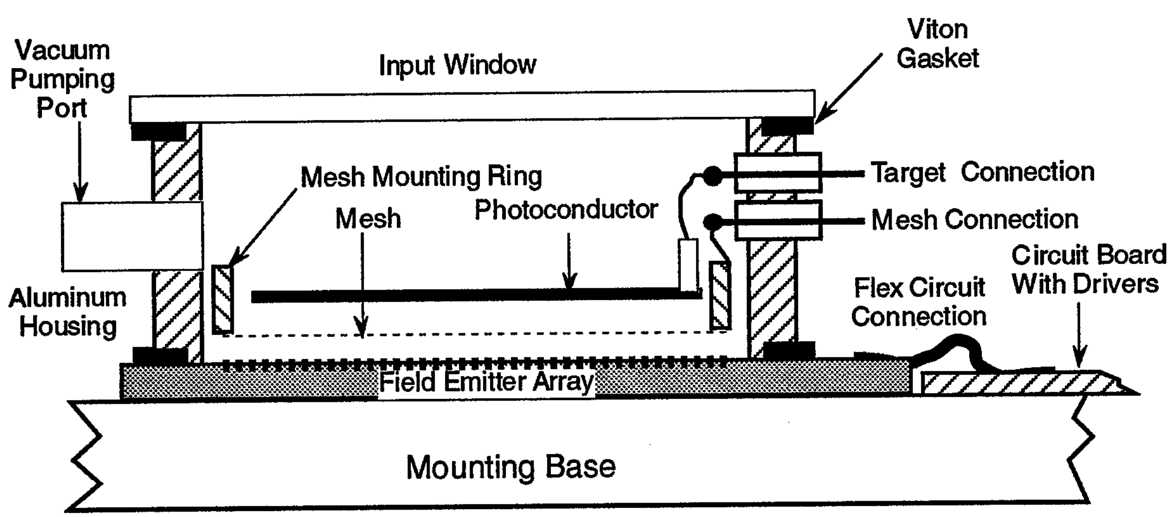


Figure 5. FEXIS Mechanical Configuration

The vacuum housing was machined out of a singe piece of aluminum and surfaces for top and bottom Viton gasket seals were polished to ensure a high vacuum seal. The Viton gaskets were located between the periphery of the array and the aluminum housing and between a 0.25" thick plate glass entrance window and the opposite end of the housing. A vacuum connection was provided to allow continuous pumping. A dry diaphragm pump coupled to a turbo-molecular drag pump produced a vacuum pressure between 10^{-7} and 10^{-8} Torr. Pressure was monitored with a standard vacuum ion gauge.

The FES employed a 0.5 micron thick crystalline antimony sulfide photoconductor layer that was deposited on a specially prepared glass substrate. The antimony sulfide photoconductor was used for many years in vidicon camera tubes so its spectral and imaging characteristics were well understood. The glass substrate was coated with a transparent conductive layer of indium tin oxide to make an electrical contact to the antimony sulfide photoconductor. During each antimony sulfide photoconductor deposition, a control sample was simultaneously produced and tested in a conventional vidicon. All of these control samples imaged well.

The field mesh was made of 500 square pitch electroformed nickel that was stretched and attached with vacuum epoxy to a square mesh support ring. The mesh was about 8 microns thick with 50% open area. The voltage for the mesh ring was delivered through a vacuum feed-through connector.

The emitter array chosen by FED, Inc. for the FES was a 480x480 square pixel device with a 125 micron pitch. This array was made with an improved process that was more robust and less sensitive to damage by air exposure than previous models. The nominal operating current for this array in a display device was a few nanoamperes. By operating the array at its maximum allowable gate voltage, it was possible to obtain currents approaching a microampere. While this was significantly lower that the current required for a FEXIS X-ray imager, it was adequate to make a demonstration device. Thus, it was decided to first test a visible imager (FES) in order to validate the FEXIS concept before attempting to use TlBr in an X-ray mode.

The Experimental Program

The objective of the experimental program was to implement the designs developed in the previous section and evaluate proof-of-concept FEXIS. A six step cooperative strategy that capitalized on the proximity of Xicon Technologies and FED, Inc. was implemented for the experimental program.

1. **Select array and perform static emission tests - FED, Inc.**
   The array candidate is hard-wired with all of the columns and gates activated and the total current is recorded. With all the pixels turned on, the current at each pixel is the total current divided by the total number of pixels. An array qualified if the total current exceeded 230 milliamperes which corresponded to a pixel current of one microampere.

2. **Bond out the array - FED, Inc.**
   The pre-qualified array is pressure bonded to flex circuits that are connected to the printed circuit driver cards. During this operation, the array is flooded with dry nitrogen to minimize tip degradation from exposure to air. The array connections are tested for shorts and opens and, if necessary, repairs are made. The tested assembly is stored under vacuum to maintain tip emission integrity.

3. **FEXIS integration - Xicon Technologies and FED, Inc.**
   Xicon delivers the vacuum housing containing the photoconductor and field mesh to FED, Inc. The vacuum housing is mated to the array and the assembly is pumped down to 10^{-7} Torr. While the device is being pumped, typically for 24 hours, the electronics are connected and tested.

4. **Preliminary test - Xicon Technologies and FED, Inc.**
   A series 100 kilohm current sampling resistor is placed in the mesh power supply line and voltage drop is monitored with an oscilloscope set to 10 mv/cm sensitivity. The target is similarly connected to a bias supply through a 100 kilohm load resistor. A test pattern projector produces an image at the photoconductor plane. Mesh current, video signal level and photoresponse are measured. Figure 6 illustrates the setup used for the preliminary measurements.

5. **Transport FEXIS assembly to Xicon Technologies**
   The tested and evacuated array assembly is isolated from the vacuum system by a high vacuum valve. The valve is closed and the assembly is removed and transported to Xicon Technologies where it is reconnected to a vacuum station and maintained at a pressure of 10^{-7} Torr.

6. **Measure FEXIS imaging performance - Xicon Technologies**
   The video electronics are connected and quantitative imaging tests are performed. The FEXIS is connected to the same digital image acquisition and processing system that was used for XEBIT measurements. MTF, resolution, dynamic range, noise and sensitivity are measured. Digital images are archived.

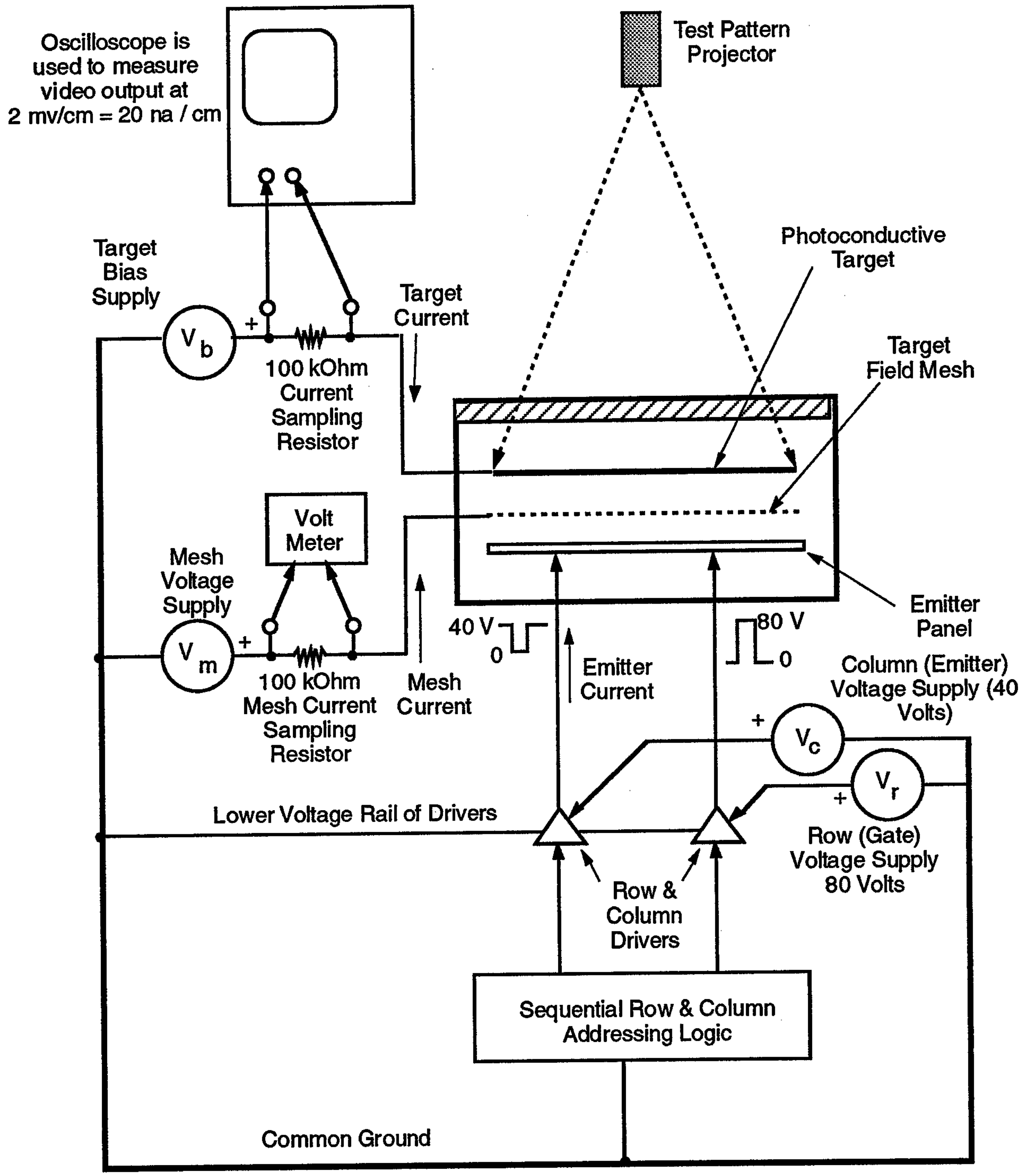


Figure 6. Schematic diagram of preliminary test setup.

Experiments and Results

Between August 1997 and January 1998, Xicon Technologies and FED, Inc., were engaged in their respective FEXIS development tasks. Between January 1998 and August 1998, three attempts to make a proof-of-concept visible field emission imager were made. Unfortunately, due to array processing problems at FED, Inc., and subsequent array performance problems, the visible imager evaluations never proceeded beyond step 4 above.

The first evaluation was attempted in February 1998. The integration went smoothly and the FES device was pumped down to 10^{-7} Torr. The emitter voltage was brought up to +40 volts and the gate voltage was set to 75 volts. The absolute maximum allowable gate voltage at which the gate drivers could be operated was +80 volts. The mesh voltage was set to 1 kV and the mesh current was measured at about 0.6 microamperes which verified electron emission. The target bias voltage was slowly brought up and the video output was monitored. There was no photo-response which indicated a problem. There was, however, a dark current signal that demonstrated that the target was being scanned. It was determined that the FED, Inc. supplied address circuits were operating at a much slower frame rate than specified and that the device would have to be disassembled to make changes to the electronics.

The address electronics were modified and re-programmed, a new mesh assembly and photoconductor target were built and tested and the system was again set up at FED, Inc., in May 1998. This time, the addressing electronics operated at the correct frame rate and a mesh current of about 1 microampere was observed. However, there was no photo-response and unlike the previous result, there was no dark current. This indicated that while the array exhibited emission, there was a possibility that selected pixels may not have been activated. The mesh current may have been from emission only at the beginning of each row since the mesh ring intercepts electrons being generated in that area. If the photoconductor was being scanned, there would have been at a minimum, a video signal due to dark current.

It was agreed to repeat the test with a new photoconductor target and mesh assembly. The device was disassembled and the array was stored under vacuum. The photoconductor was removed and independently tested in a conventional vidicon. It imaged well and dark current was nominal, a few nanoamperes. A new antimony sulfide photoconductor was deposited on a glass substrate and a new field mesh assembly was prepared. The photoresponse and resolution of the control sample that was simultaneously deposited were verified in a vidicon. The tested assembly was taken to FED, Inc., in June and integrated with the array that had been under vacuum in the intervening period.

The initial results were the same as those of the previous test, no dark current and no photoresponse. It was decided to slow down the clock frequency in case the array was being driven too fast to allow complete gate and tip switching. As testing proceeded, it was noticed that the vacuum housing was getting warm. This was attributed to the higher than normal tip current and IR losses due to high capacitive charging currents on the internal array bus lines. After about 30 minutes, there was a loud crack and the vacuum pump started to slow down. A catastrophic leak had developed and the vacuum system was turned off to prevent turbo pump damage.

Upon investigation, it was found that the emitter array had cracked due to local heating. This event brought all testing to a halt since there were no other arrays available. A new array was to be made available by the end of October. It was decided to bond the next array to a heat sink to prevent localized heating and the resultant mechanical stress.

The experimental results to date are inconclusive. While experimental progress has been disappointing, there is no fundamental reason to believe that an imaging device cannot be built using a field emitter array. During the first test, dark current was observed, but the frame rate was so slow that the device remained in saturation. The failure of the two subsequent tests using a new array, (the same array was used for the last two tests) are believed to be due to emission anomalies. The fact the array cracked indicates a high leakage current developed at a localized site. This could have easily disrupted the array potentials resulting in emission anomalies. The most likely event is that the array was emitting perhaps at the region around the heating anomaly. The next test is scheduled for late October.

Objective 2 and 3: Analyze numerically and experimentally alternative structures for the read-out to optimize performance for the mammography application.

This work focused on the analysis of a mammography FEXIS as opposed to a general radiographic device. Mammography is a special procedure that places some very challenging requirements on the sensor. During the prototype system analysis phase, it became apparent that field emitter technology was less advanced than had been first thought. The high beam currents being proposed for the FEXIS device would not be feasible in a field emitter array within the foreseeable future. The 50 micron pixel pitch that would be ultimately required in a mammography FEXIS would not be achievable with contemporary field emitter panels. Furthermore, there was no reason for FED companies to make emitter panels with a pixel pitch less than 125 microns since that was sufficient for display devices. The following discussion focuses on the development of a realizable mammography sensor based on an innovative application of contemporary field emitter technology.

Mammography procedures are done at low X-ray energies, typically 18.5 kV, with generally high fluence levels and require high resolution (10 lp/mm). As a starting point for exploring FEXIS mammography structures, the requirements below were developed.

Mammography FEXIS Requirements

Imaging Area	10" x 10" (250 mm x 250 mm)
Pixel Size	Square, 0.002" x 0.002" (50 microns x 50 microns)
Nyquist Limiting Resolution	254 line pairs per inch (10 line pairs per mm)
Minimum DQE	95% Minimum
Maximum Readout Time	2 Seconds (independent of X-ray exposure time) The X-ray exposure would be the same or likely less than that required with other mammography sensors.
Form Factor	Generally a flat panel consistent adaptable to existing mammography systems due to the FEXIS high DQE and superior contrast resolution.

The quantum absorption of 18.5 keV photons by a 60 micron thick TlBr layer is 100% based on absorption measurements and the published linear absorption coefficient for this material. XEBIT measurements indicated that virtually all the photon generated charge can be collected with a field of 1 volt / micron across the TlBr layer. This corresponds to a target bias voltage of 60 volts for the 60 micron thick target. At high fluence levels, some charge may be lost through recombination which tends to compress the linearity. This effect is helpful because it acts like an automatic gain control that softens the onset of saturation and extends dynamic range. In a typical

mammography procedure, the incident fluence on the detector is 10 milli-Roentgen at 18.5 keV which equates to 516,884 X-ray photons per square millimeter. A one millimeter thick beryllium X-ray window absorbs about 7% of the X-rays which reduces the input fluence to 480,700 per square millimeter or 1202 photons per 50 x 50 micron pixel. An energy of 6.5 eV is required to create a hole-electron pair in TlBr[1], so the gain of TlBr at 18.5 keV is 2846 electrons per absorbed photon.

The total number of electrons, Ne, generated in a 50 x 50 micron pixel area then is:

Ne = Number of Photons x Conversion Gain

This calculation yields 3.42×10^6 electron-hole pairs per pixel.

Assuming a 5000 x 5000 pixel array (250 mm sensor with 50 micron pixels) and a 2.0 second readout time (a readout time of 2.0 seconds is reasonable for a mammogram), the pixel dwell time is 80 nanoseconds (12.5 MHz pixel read frequency). Note that the readout time is independent of the X-ray exposure time and that the total time for a mammogram is the sum of the readout time and the X-ray exposure time. Given the readout timing above, the scanning electron beam then must replace the total amount of charge generated in each pixel by X-ray photons in 80 nanoseconds. The minimum required beam current, I_b then can be calculated:

I_b = Number of Electrons/Pixel x Electronic Charge / Pixel Dwell Time

I_b = 6.85 Microamperes Applying the 4X beam reserve factor of 4X and the 50% mesh loss, the actual beam current required is 54.8 Microamperes.

This level of beam current in a 50 micron pixel is not attainable in practical field emission devices although the emitter tips are capable of very high current densities. In general, as tip current is increased, current stability becomes a problem so series resistive elements are integrated into the emitter structure to limit and stabilize tip current. More relevant to this discussion is the fact that the panel cannot be readout at the required 12.5 MHz addressing frequency.

Parallel Readout Options

The possibility of segmenting the target to capitalize on the multiplex option that the flat emitter panel offers led to the investigation of a parallel readout scheme. A 5000 x 5000 pixel mammography FEXIS is illustrated in Figure 7a. The function of rows and columns has been transposed from that in the prototype case to facilitate the discussion of the segmented target concept illustrated in Figure 7b. An interleaved connection is shown because no field emitter panel manufacturer can meet the 50 micron pixel pitch requirement due to connector density limitations. By connecting only the odd lines on one side of the panel to drivers and the even lines on the opposite side of the panel to respective drivers it is possible to produce a 100 micron connector pitch in a 50 micron pixel device. This is about the minimum pitch density that flat panel manufacturers are able to deal with in the panel connection system. While the requirement for 5000 drivers on the row and column lines seems difficult, the LCD display industry has driven the development of low cost high density integrated circuit drivers that can be used for flat panel emitters.

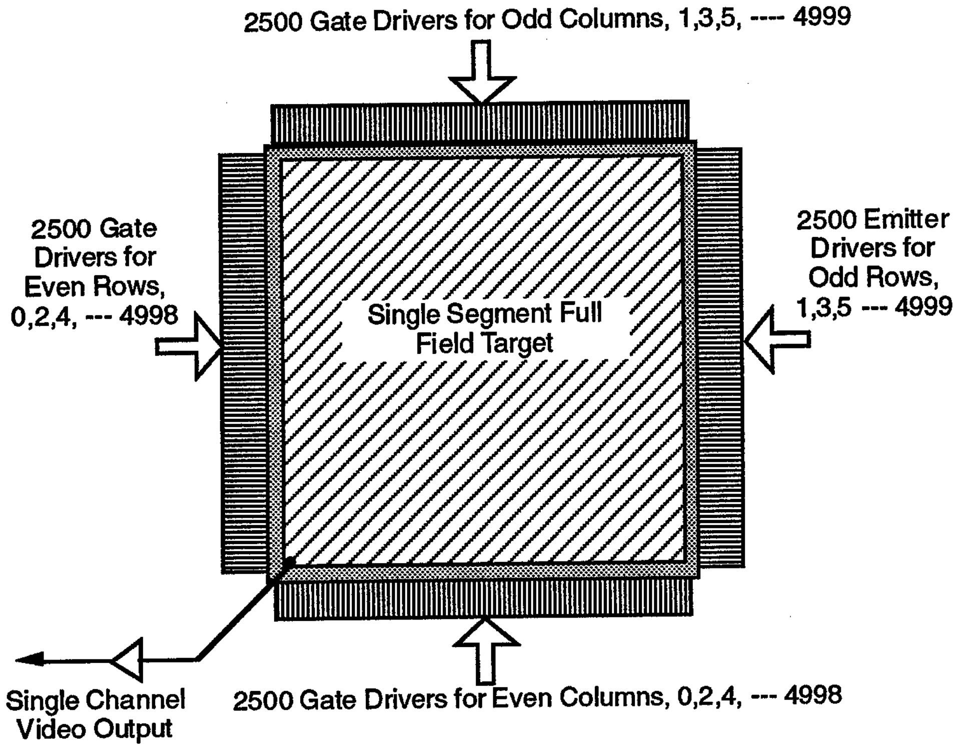


Figure 7a. Single target mammography sensor.

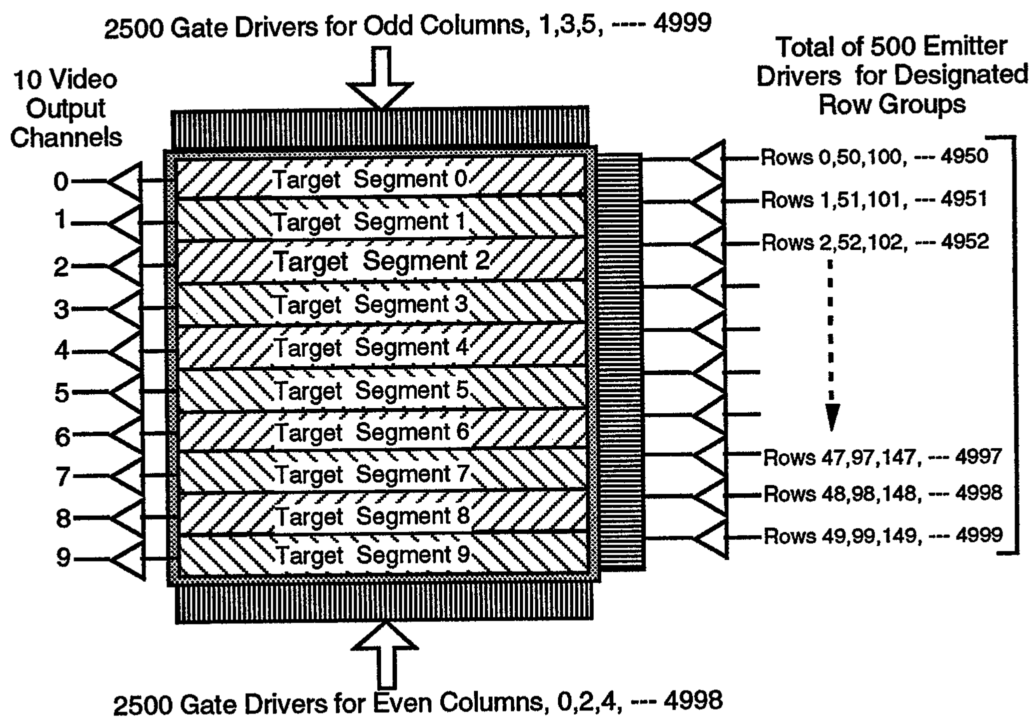


Figure 7b. Target segmentation that allows equivalent pixel rates of 12.5 MHz. The structure illustrated in Figure 7b, employs a target that is split into 10 segments that feed 10 video amplifiers operating in parallel. The columns are interleaved similarly to those in Figure 7a, to achieve the 50 micron column gate spacing. The rows, however, are mapped to emitter drivers as indicated so that 10 pixels under the active gate are read simultaneously. By employing 10 target segments, the number of row drivers is reduced by 10X and the row connection problem is greatly mitigated. The interconnections of the parallel rows can be accomplished in a printed circuit between the drivers and the panel so that number of external connections is reduced from 5000 to 500. Note that each of the 500 emitter drivers need only supply current for one pixel at a time.

By using 10 segments, the addressing speed to read out the entire 5000 x 5000 pixel array has been reduced from 12.5 MHz to 1.25 MHz. This is still three times higher than the 400 kHz addressing frequency constraint imposed by the array and drivers . By increasing the number of segments from 10 to 32, it is possible to readout the entire array in 2 seconds while meeting the 400 kHz restriction. This segmented approach also provides a solution to the high beam current problem that would result with a 12.5 mHz readout. The pixel dwell time is increased by a factor of 32 so that the beam current on a pixel basis is reduced by a factor of 32 from 58.8 microamperes to a more manageable level of 1.84 microamperes. Thus, a practical mammography FEXIS is feasible by employing interleaved geometry on the columns and by capitalizing on the segmented target.

Resolution Considerations

A device made in this way, however, may not exhibit the required 10 lp/mm spatial resolution. The TlBr photoconductor is capable of 60 lp/mm resolution so FEXIS resolution is dictated solely by the electron beam geometry. Based on the current knowledge of field emitter behavior, achieving 50 micron resolution is the most challenging problem in this program. Figure 8a illustrates the conventional triode field emitter tip and gate configuration. In a field emitter display device, the phosphor screen is operated typically at 4 kV to obtain the brightness necessary to compete with CRTs. This requirement is not consistent with close spacing between the emitter and the phosphor screen due to a potential for flashover. If the phosphor screen is spaced out at a reasonable distance, 2 millimeters for example, the electron beam spread significantly degrades spatial resolution. Thus, the next generation of field emitter display panels will be built in a tetrode configuration to achieve the necessary electron beam collimation. The additional electrode that is used to focus the electrons into well collimated beams is conceptually illustrated in Figure 8b. Some array manufacturers are already making small tetrode emitter panels, but a significant amount of development work still remains, especially for larger arrays. The mammography FEXIS will not be feasible until good collimation has been achieved in 10 inch display devices which fortunately, is the FED industry trend.

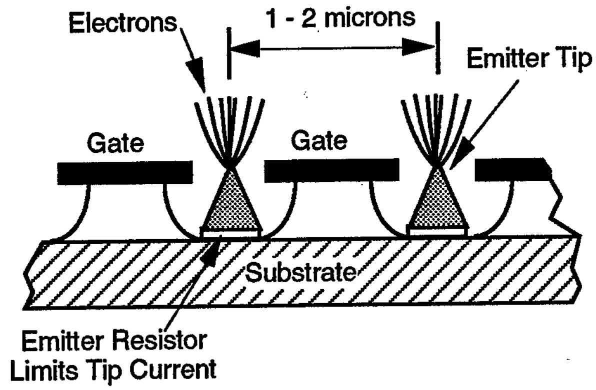


Figure 8a. Cold cathode field emitter triode configuration. In a display, the phosphor forms the third electrode. Note that only two tips are shown, but that there may be as many as 200 emitter tips in a single 50 micron pixel . The angular spread of emitted electrons results in a large electron beam spot size and degraded resolution. Based on computer simulations, a 2.75 millimeter spacing between the TlBr target and a contemporary single gate emitter panel would result in a beam spot size approaching 2.5 millimeters.

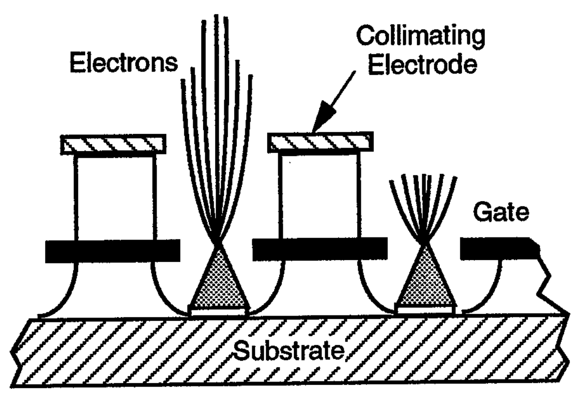


Figure 8b. The tetrode configuration employs a second gate to produce a collimated electron beam. This addition greatly complicates the manufacturing process, but is necessary in display devices to allow greater spacing between the phosphor screen and the emitter substrate, thus reducing the possibility for catastrophic failure due to high voltage flashover.

Dr. Cha-Mei Tang, an electron optics consultant to the program, made a number of electron trajectory simulations that support the need for better collimation. The results of Dr. Tang's simulations are included herein as Appendix A. In summary, the simulations showed that with a 1.5 mm spacing between the emitter panel and the field mesh and a 1.5 mm spacing between the field mesh and the photoconductive target the beam will spread out to about 3 mm. This result is unacceptable since the beam spot size must be comparable to a pixel dimension. The mesh and photoconductor spacings can be reduced to reduce beam spot size, but the capacitance between the target and the mesh would be significantly increased and preamplifier noise contribution increases with source capacitance.

Noise Considerations
Noise in an imaging system arises out of two basic sources. The first is the intrinsic photon statistical noise in the input signal often referred to as "shot noise" that is equal to the square root of the number of incident photons in a given sample. The second is noise introduced by the electronics and readout system. The system noise should be less than the statistical photon noise so that the system is always photon noise limited. It has been shown[3] that the XEBIT operates in a photon noise limited regime and the FEXIS should similarly do so.

The input signal is 1202 photons per pixel

The noise in the input signal is then $(1202)^{1/2}$ noise photons per pixel

The input signal to noise ratio (SNR) is then 35 : 1

The video bandwidth f, of the 32 video channel segmented FEXIS, is 400 kHz. A typical value for the target load resistor R_f, is 50 kilohms and the transconductance of the preamplifier input device is typically 20 mmho. The input source capacitance C_i, formed by the target signal plate and surrounding structure, for the non-segmented FEXIS with a 1.5 mm target-to-mesh spacing is about 400 pf. For the case where the target is made in 32 segments, C_i is theoretically reduced to about 13 pf however, there is about 5 pf of stray capacitance associated with each segment so the value of C_i is more like 18 pf. Using these values and the following expression[3] the preamplifier noise can be calculated.

$$I_{np} = [\, 4\, k\, T\;\, f \;\; \{ (1/R_f) = (2\, \pi\, f\, C_i)^2 / 3G_m \} \,]^{1/2}$$

$$I_{np} = 400 \text{ Picoamperes}$$

The output signal current, Is, can be calculated.

Is = (Number of Electrons in a Pixel) X (Electronic Charge)/ Dwell Time

Is = 214 Nanoamperes

The system output signal-to-noise ratio is then

$$\text{SNR} = \text{Is} / I_{np} = 535 : 1$$

This is significantly higher than the input SNR of 35 : 1 so the segmented target system will operate in a photon noise limited regime and system noise should not present a problem at typical mammography fluence levels.

In order to minimize beam spreading, it is preferable to reduce mesh and target spacing as much as possible. As a practical matter, 0.5 mm is probably the minimum target-to-mesh spacing that can be achieved. The input source capacitance C_i, added to 5 pf of stray capacitance would be about 44 pf and the system SNR would decrease to about 192 : 1, still a respectable level.

Conclusions

We have explored the feasibility of making a mammography imaging sensor by combining a TlBr photoconductor with an addressable array of cold cathode field emitters in a novel **F**ield **E**mission **X**-ray **I**maging **S**ystem (FEXIS). While a variety of emitter array problems prevented us from performing the necessary experiments to support the case for this sensor, we were able to develop an approach that should work when field emitter panels are available. The structures illustrated in Figure 7 can be built given the availability of suitable field emitter arrays. The high beam current required by a full target FEXIS can be reduced to acceptable levels by segmenting the target. This has the added advantage of reduced video bandwidth and thus, lower system noise.

There are two major obstacles that are preventing the development of a 50 micron pixel FEXIS mammography sensor.

The first is the poor collimation of field emitter arrays that will reduce spatial resolution to an unacceptable level. It is our understanding that FED manufacturers are developing collimation techniques that will allow the phosphor screen to be placed possibly several millimeters away from the array. High brightness FEDs with high spatial resolution will not be feasible until the electron beam collimation is significantly improved. The mammography FEXIS will become feasible when these displays become available.

Secondly, a FEXIS implementation will stretch the limits of device design rules by requiring a 50 micron pitch across a 250 millimeter panel. While it may be possible to connect drivers to the array as illustrated in Figure 5, the small internal conductor cross section will ultimately limit the maximum available beam current. It is believed that FED manufacturers may stop at a pixel pitch of 100 microns since there is no obvious need for a finer pitch device in a large area display. Miniature displays will likely employ solid state LED technology that is more amenable to the production of fine pitch devices.

It was hoped that the mammography FEXIS could leverage off existing FED designs and a suitable emitter array could be produced with only simple process modifications. Given the limitations above, it is clear that to make a practical FEXIS mammography sensor, a customized field emitter array that stretches array process technology will have to be designed and built. The development costs for such an array would exceed the funding levels of this contract, but it would be considered as a follow-on option for production.

We believe that the FEXIS market opportunity is large enough to justify the cost of developing a custom device when emitter array technology is further along. Within two years, field emitter array technology should be mature enough to commit to a custom array design meeting the mammography requirements. In the meantime, a FEXIS mammography sensor with 100 micron pixels based on contemporary FED design rules is feasible.

In the past year we have made great progress in the development of a process for making TlBr photoconductor films up to 9" in diameter. The high DQE, superior spatial

resolution, wide dynamic range and unprecedented contrast resolution that were predicted have been verified in XEBIT based imaging systems. It has been frustrating to not be able to mate our photoconductor technology with a flat panel readout device because it should be technically feasible.

The main concern with the continuation of this program is the inability to obtain field emitter arrays in a timely manner. The FED, Inc. relationship has not been satisfactory and between delivery delays and lack of follow on support we believe it is advisable to look toward alternative flat panel readout options. We have been unable to interest any of the other FED companies listed in Appendix B in this program. This is understandable because they are totally focused on their own display product development problems in a very competitive business environment. All of the companies contacted felt that the FEXIS was a viable and exciting application of field emitter technology.

Xicon Technologies is committed to the embodiment of the TlBr technology in a flat panel configuration for mammography and for the general radiology market as well. To that end, we will be proposing an alternative approach to the development of a flat panel TlBr mammography sensor that will meet the original program objectives within the original budget.

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APPENDIX A

Survey of Field Emitter Arrays for Field Emission X-ray Imaging Sensor (FEXIS)

Cha-Mei Tang

Field emitter arrays (FEAs) have the potential of achieving the FEXIS specifications. The FEAs are currently under intense development by a number of domestic and international field emitter display (FED) companies. The cost of the development is very high (tens of millions of dollars per company per year) and the development time is long. The specifications for FEDs and FEXIS share many similarities. FEXIS can greatly benefit from FED achievements. This is a survey of large area FEA and their potential applications to FEXIS. In this survey, the emphases are on pixel resolution, beam collimation and beam current.

Presently, none of the FED display companies have FED models which meet FEXIS specifications of 100 μm × 100 μm pixel resolution and 100 μA current. These companies are very focused on the development of FEAs for displays and are not distracted by other potential applications for FEAs. The most advanced FED development comes from a consortium formed by PixTech (France), Raytheon (USA), Motorola (USA) and Futaba (Japan) [PixTech 1997, Futaba 1997, Tanaka et al. 1997, Raytheon 1997, Credelle and Moehring 1997, Young 1996]. Texas Instrument was a member of the consortium until they decided not to develop FEDs last year. The goal of the consortium is to speed the introduction of FEDs into the market by pooling all their intellectual property and research effort as a team for a limited number of years. Within the consortium, PixTech supplies the FEAs. At the same time, Motorola and Futaba also have their own FEA fabrication facilities and they are improving their own FEA processing techniques. The first FED product introduced into the market was by PixTech this year. Raytheon has working demonstration prototype models. Futaba has FEDs available for evaluation. Motorola is keeping its development very secretive; their Flat-Panel Display Division moved into a new dedicated display fabrication plant this summer.

There are currently three other FED display companies in the United States: FED Corp., Candescent Technology Corp. (former Silicon Video) and Micron Display Technology, Inc. [FED 1997, Micron 1996] Micron is close to introducing viewfinder FEDs into the market. Candescent is showing its model displays in private. FED Corp is behind the pack; they are concentrating on small avionics displays. Two other U.S. FED companies dropped out of the FED business last year: Color Ray went bankrupt and SI Diamond is concentrating on large pixel billboard displays for the near future.

Two additional organizations outside the U.S. committed to the development of FEDs are Samsung (Korea) and ERSO/ITRI (Taiwan) [Kim et al. 1997, Tsai et al. 1997]. Samsung has considerable financial and organizational resources and is aggressively developing FEDs. ERSO/ITRI is primarily supported by government funding. Both have prototype models of color displays.

There are many organizations that can fabrication small arrays of FEAs: SRI International, MCNC, Varian, etc. The size is limited by the substrate size of the fabrication equipment.

Pixel Resolution

Electrons emitted from the tips of FEAs have large angular spread. Left uncontrolled, the angular spread causes the FEAs fail to meet the beam collimation and pixel size requirement of FEXIS. The subpixel resolution of all FEDs under development by all FED companies are in the range of 118 μm to 330 μm, with the exception of the subpixel of Micron's 0.7" viewfinder, which is 37 μm. Currently however, the FED companies are more concerned in introducing a product into the market place rather than with picutre resolution. Their philosophy is that beam collimation with integrated lenses is research, not product development.

In the future, all FED companies will have to reduce their pixel size to achieve high resolution. When that happens, the results will benefit FEXIS.

It is important to note that the actual size of the electron beam spot on the anode in a FED display is almost always much larger than the subpixel size. The reason is that FED displays use a black matrix to provide contrast and light is generated on the phosphor spot between the gridwork of the black matrix. For example, Samsung's demonstration display has a 100 μm wide black matrix around 100 μm wide strips of phosphor. The beam width is actually about 300 μm wide.

The requirement of beam collimation for FEXIS is more stringent than for FED displays even for the same pixel resolution.

Summary of Beam Collimation Methods

Lens design is critical to the achievement of good beam collimation. Inadequate lens design can lead to one or more of the following problems: significant reduction of emission current, poor focus, a limited area where the emitters can be located (a small "sweet spot"), low packing density, difficulties in manufacturing, and loss of emitted electrons to the gate, lens electrodes, and insulators.

A short summary of beam collimation methods and their drawbacks is presented below. These methods include proximity focusing, macroscopic lenses, and integrated lenses.

1. Proximity focusing is achieved by placing the anode very close to the FEA. The electrons do not have a chance to spread due to the short distance between the anode and cathode. For some applications, further reduction in pixel size is achieved by

applying voltages on the phosphor dots. In order to avoid flashover, the phosphor voltage has to be low. PixTech and Micron use proximity focusing. Proximity focusing is not applicable to FEXIS.

2. Macroscopic-Lenses for each pixel means that a single lens opening is used to collimate all the emitters in the pixel. Macro-lenses can take the form of:

- thin tall lenses such as those used by Candescent,
- integrated macro-lenses,
- or large flat electrodes with holes like those of Raytheon.

For all macro-lenses, only those field emitters located within a small spot can be focused.

<u>Thin Tall Lenses</u>

- Candescent calls this small spot the "sweet spot." Electrons from field emitters located outside the sweet spot will be bent towards the gate, towards the lens, or towards the wrong pixel. The tall lens walls can catch stray electrons from the sweet spot. The disadvantages of this structure are: additional fabrication costs for the high aspect ratio electrodes, assembly of the lens electrode on top of the FEA <u>after</u> fabrication of the FEA, and the small sweet spot.

<u>Integrated Macro-Lenses</u>

- Large, planar macro lens fabricated on the FEA surrounding all the emitters in a pixel is another concept. For integrated macro-lenses, the area of the lens electrode has to be large so that the focusing field that it produces can be extended to a height comparable to the lens opening width. The beam collimation of an integrated planar lens is slightly less favorable than that of a tall macroscopic lens because electrons from tips outside the sweet spot can lead to stray beams without a tall lens to block their path. Also, the conceptual sweet spot is smaller than that of the tall macroscopic lens. However, integrated planar lenses are much easier to fabricate and manufacture.

<u>Large Flat Electrodes</u>

- Raytheon's lens design is in-between a tall lens and an integrated macro-lens. Raytheon's lens requires the field emitters to be located within a sweet spot. Surface mounting of the lens to the completed FEA may be problematic. Insulating cement material is necessary to attach the lens to the FEA to prevent vibration of the lens in acceleration. The application of the insulating cement material, without damaging the field emitter tips, may be tricky. In addition, the thermal expansion and stress coefficients of the FEA substrate, the macro-lens and the cement materials have to be carefully matched for the thermal cycles during the final vacuum sealing. Mismatch of the stress coefficients can cause cracking of the substrate, bulging of the lens, and separation of the lens from the substrate.

3. Integrated lenses around each emitter, fabricated at the same time as the FEAs, would give the best beam collimation. A variety of integrated lenses are under development by several research groups. The most common lens design has the lens

electrode above the gate electrode, as shown in Fig. 1. Private communications indicate designs of this type have been or will be fabricated by Electrotechnical Laboratory of Japan, ERSO/ITRI of Taiwan, SRI, Creatv MicroTech, and others.

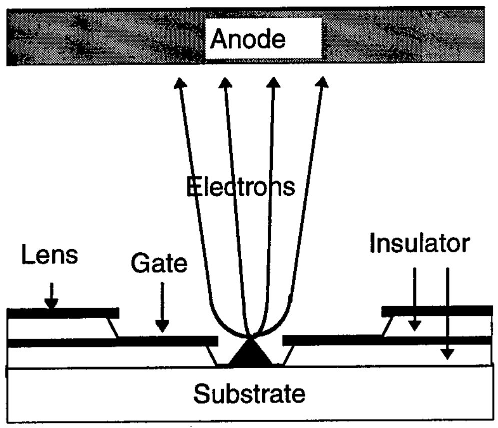

Fig. 1 Typical integrated lens with a gated field emitter.

Fabrication and experimental test results of a self-aligned integrated lens of the type displayed in Fig. 1 has been reported by a group headed by Itoh [Itoh et al. 1994, Toma et al. 1996] for silicon field emitters. In their design, the lens opening diameter is 2.2 μm and the gate opening diameter is 1.2 μm. The intensity of the beam transmitted through the lens opening decreases by about two to three orders of magnitude as the beam becomes focused. This reduction in the current at the anode is caused primarily by the inability of the electrons emitted at an angle to pass through the lens opening, and to a lesser extent by the reduced emission at the tip caused by the low lens field. Better lens design will allow the beam to propagate out of the lens opening.

Electron beams from field emitter tips were focused in one-dimension to form sheet beams [Tang and Swyden 1997]. Experimental data indicating the FWHM is 33 μm at the anode placed 10 mm away at 2.5 kV. The results are in good agreement with simulation. This indicates that integrated lenses can focus the electron beam.

When the desirable pixel resolution is 50 μm × 50 μm, macro lenses becomes difficult to fabricate and assemble (Candescent and Raytheon). Three-dimensional simulations show that very good beam collimations can be obtained by appropriately designed integrated lens around each tip. The beam collimation from integrated lens can be better than that from macro-lenses.

The lack of encouraging results thus far for beam collimation from integrated lenses at the present time does not mean that it is not a good approach. However, the processing development may be long and expensive. Since various researchers are pursuing integrated lenses, FEA with integrated lenses will be developed in the future. In the long run, FEA with integrated lenses will be the best approach to obtaining the required beam collimation for FEXIS.

A summary of domestic field-emission displays is given in Table I; and a summary of foreign field emission displays companies is given in Table II.

Diamond Field Emission

Diamond Field Emission has received considerable attention as a potential FED cathode. However, the research results are not encouraging.

Beam Current per Pixel

The current requirement for FEXIS is 100 μA per pixel, which is much larger than the current requirement for displays. Emissions from single tips on the order of 10 μA are common for silicon and metal tips made for microwave amplifier applications. The gate voltages are on the order of 100 V relative to the tip voltage (no resistive substrate). In principle, 100 μA should be achievable within a 50 μm × 50 μm pixel area.

The field emission current increases faster than an exponential function of the gate voltage. This function is very sensitive to variations in tip geometry. Since not all the tips can be identical in shape in atomic scale, small variations of the tip geometry can result in different amount of emission from each tip. This variation also causes catastrophic tip blow-up as total current is increased. The common solution is to provide a resistive substrate to the tips. The high resistance reduces the sharp rise of the current as the gate voltage increases. Resistive substrate also enables more tips to emit, and the amount of emission current from each tip is more uniform. Thus the highly resistive substrate provides tip protection and also array uniformity. When the resistive substrate is used, however, the gate voltage has to be increased in order to obtain the same emission current.

For cost and timeliness reasons, it is important to be able to drive FEAs with display drivers. Typically, the display drivers switch tens of volts, not hundreds of volts. In order to switch 100 μA per pixel with tens of volts, the following two options can be tried: (i) reduce the work function of the emitter tip and (ii) reduce the resistivity of the substrate.

Slight reduction of the resistivity of the substrate will still provide tip blow-up protection, but it will provide less current uniformity. For FEXIS, current uniformity is not critical as long as it meets the minimum value.

The work functions of metal tips are typically on the order of 4.6 eV. If the work functions of the tips are reduced, the FEAs with the same geometry and the same gate voltage will be able to deliver much more current. Mackie and Davis of Linfield College have shown that coating metal and silicon tips with a very thin layer of ZrC reduces the work function by approximately 1 eV [Charbonnier 1997]. This reduction in work function will reduce the gate voltage requirement.

In conclusion, it is possible to drive FEAs with display drivers and obtain 100 μA of current per pixel. To accomplish this, FEAs will require further development.

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Table I: Summary of Domestic Field Emission Display Companies

Company and Contact	Size	Resolution	Pixel Sizes (μm)	Comments
FED Corp. 1580 Route 52 Hopewell Junction, NY 12533 (914)892-1FED fax: (914)892-1901	3ATI: 57 mm x 57 mm full color	240 x 240	subpixel: 118 x 118	Macro focusing with integrated lens
Candescent Technology Corp. 6320 San Ignacio Ave. San Jose, CA 95119 (408)229-6150 Robert Duboc Ex. VP/COO	1.75” diagonal full color 6” Development line; 320x340 mm Development line	100 x 100 ??	315 x 315 3 color ??	Phosphor voltage: 4 kV to 5 KV Tall macro lenses assembled after FEAs are fabricated.
Raytheon Electronic Systems 465 Centre Street Quincy, MA 02169 (617)984-8529 fax: (617)984-4196 Alan Palevsky (617)984-8238	4” x 4” monochrome 6” x 6” full color	512 x 512 512 x 512	198 x 198 4 color quad: 300 x 300 subpixel: 150 x 150	High voltage phosphor Macro focusing with separate lens

VGA: 640 x 480 pixels; Super VGA: 1024 x 768; XGA: 1280 x 1024;

Table I: Summary of Domestic Field Emission Display Companies (Continued)

Company and Contact	Size	Resolution	Pixel Sizes (μm)	Comments
Motorola Flat Panel Display Division 770 S. River Parkway Tempe, AZ 85284 Mr. Thomas L. Credelle Director of Marketing (602) 755-5511 fax: (602)755-5502	??	??	??	In house integrated focusing lens development is unsatisfactory. Robert Smith wrote letter of support for my proposal to DARPA.
Micron Display Technology, Inc. 3000 S. Denver Way Boise, ID 83705 (208)333-7500 Mr. Duane Richter David Cathey, Jr., President (?)	• 0.7" diagonal full color • 12 inch diagonal full color in development	240x(140x3) 1280 x 1024	37 x 37 3 color: 200 x 200 subpixel could be 100 x 100	Richter may be interested in applications of field emitter arrays for other applications. Low voltage phosphor about 1-2.5 kV, proximity focusing. Claim no focusing lenses used. Spacers: 25 μm wide 350 μm tall 40 μm tall 2400 μm tall

Table II: Summary of Foreign Field Emission Display Companies

Company and Contact	Size	Resolution	Pixel Sizes (μm)	Comments
PixTech 3350 Scott Boulevard, Bldg. 37 Santa Clara, CA 95054 (408)986-8868 fax: (408)986-9896 http://www.pixtech.com	• FE532M & FE532HB: 4.03"×3.02" • FE85XM: 8.5" monochrome • FE85YC: 8.5" full color	320/240 320/240 640x480 640x480	330 × 330 330 × 330 280 x 240 3 color 280x240	Only interested in selling displays. Not interested in other products Low voltage phosphor, proximity focusing
Futaba Corporate Marketing & Sales Div. M.T.G. Bldg, Bldg.B-6F 1-3 Nakase, Mihamaku Chiba City, 261-01 Japan 043-296-5111 fax: 043-296-5122	• F320A240AAA: 99.2 mm x 74.4 mm blue-green • F320B240AAA: (2) mm x 86.4 mm blue-green • Demo: 98.88 mm x 74.16 mm	320 x 240 320 x 240 320 x 240	310 x 310 360 x 360 subpixel: 103 x 309	Low voltage phosphor, phosphor screen. Dual anode drive for demo.
Samsung Advanced Intitute of Technology P) O. Box 111 Suwon 440-600 Korea Dr. Jong Min Kim Director Display Materials Lab. 82-331-280-9311 fax: 82-331-280-934	64 mm x 64 mm 3 full color	128 x 128	3 color: 500 x 500 subpixel: 100 x 500	Low voltage phosphor (250 V) Beam is actually (>300 μm x 500 μm).

Prepared by Cha-Mei Tang for Xicon.

Table II: Summary of Foreign Field Emission Display Companies (Continued)

Company and Contact	Size	Resolution	Pixel Sizes (μm)	Comments
ERSO/ITRI Taiwan Republic of China	55 mm x 40 mm		subpixel: 330 x 330	5 mm gap; phosphor screen 5 kV; beam resolution 450 μm
Canon Research Center Kanagawa, Japan E. Yamaguchi	156 mm x 208.8 mm (10 inch diagonal) full color	240x240x3	subpixel: 290 x 650	Alternative large area electron beam source with natural focusing, but may be limited in current

APPENDIX B

Simulations of Field Emitter Arrays for Field Emission X-ray Imaging Sensor (FEXIS)

Cha-Mei Tang

This report presents the results of the study on electron beam transport from field emitter arrays (FEAs) to photoconductors for application to x-ray imaging sensors. This effort consisted of four parts:

- Performing three-dimensional simulations of electron trajectories from field emitter tips up to a distance of 150 μm from the FEAs.
- Performing analytical calculations of the electron trajectories from 150 μm from the FEAs to the mesh based on data from the simulation code. Obtaining the beam size and trajectory angle of the electron beam at the mesh.
- Performing three-dimensional simulations of the electron beam trajectories going through the mesh.
- Performing three-dimensional simulations of the electron beam propagation from the mesh to the photoconductor.

Comments on the simulation results and their implications for FEXIS are included.

Three-dimensional Simulation of the FEA

The 3D simulations of the FEA were based on a set of FED parameters. These parameters may not have corresponded exactly to the parameters of the field emission array that FED Corp. had given to Xicon for testing, but they were similar. The differences are not of significance to this project. (The details of the pixel layout are not given here, because it is proprietary and confidential to FED Corp.) The emission was chosen from a tip located at (x=15.0 μm, y=0.0 μm) from the center of the pixel.

MEBS Software, EO-3D, was used to calculate the equipotential and the electron trajectories near the field emitters. The 3D simulation volume for the "EO-3D" Code was (118 μm, 118 μm, 150 μm) for (x,y,z) coordinates. The electron trajectories outside this simulation volume were calculated analytically. The electron trajectories were plotted only for electrons, which were emitted initially on the x-axis, the y-axis, and at a 45° angle, corresponding to the blue, black, and red trajectories, respectively. Initially, the angular spread was from –40° to +40° in 5° intervals from the top of the tip. For smooth emitter tips, the emission angle would be much smaller than –40° to +40°. For metal tips, however, the emission angle could be large because the tips are more irregular.

For display applications, the current requirement is low; thus a lower gate-to-substrate voltage can be used. For the following parameters: gate voltage at 55 V, phosphor screen at 1 mm at 4.9kV, and the tip at ground level, the electron beam emitted from a ±20° angle has a spread of only about 150 μm at the phosphor screen.

For the FEXIS application, there are a number of differences; the current requirement is higher; the gate electrode-to-substrate voltage is 120 V. Since FED Corp uses resistive substrates to

stabilize the emission, the voltage from the gate to the top of the emitter tip is much lower. We will assume the voltage drop from the gate to the top of the emitter tip is 65 V, which is probably on the low side. In the experiment, the FEA to mesh distance had a range of 2.5 mm to 3.0 mm. For simulation purposes, the mesh to FEA distance was set at 2.75 mm, and the mesh was set to 3.0kV. In the experiment, the mesh was held between 2 kV to 3 kV.

Figure 1 is a plot of the electron trajectories and equipotential curves for the emitter tip in the y-z plane through x=0 obtained by EO-3D. The tip is located at y=0, the center of the pixel in the y-direction. The equipotential curves are plotted in 25 V intervals. The electron trajectories are the y-z projections for all x.

Figure 2 is a plot of the electron trajectories and equipotential curves for the emitter tip in the x-z plane through y=0 obtained by EO-3D. The tip is located at x=15 μm from the center of the pixel in the x-direction. The equipotential curves are plotted in 25 V intervals. The electron trajectories are the x-z projections for all y.

Figure 3 is a plot of the electron trajectories and equipotential curves for the emitter tip in the x-y plane through z = 5 μm obtained by EO-3D. The equipotential curves are arbitrarily spaced. The electron trajectories are the x-y projections for all z.

Analytical Calculations of the Electron Trajectories to the Mesh

Using the data from EO-3D, we calculated analytically the electron trajectories outside the simulation region to the mesh.

Figure 4 is a plot of the location of the electrons on the mesh located at 2.75 mm from the array at 3 kV. When the emission angle at the tip is ±20°, the spot size on the mesh is about 0.75 mm; when the emission angle at the tip is ±40°, the spot size on the mesh is about 1.5 mm.

Figure 5 is a plot of the angular spread, vx/vz, of the electrons at the mesh located at 2.75 mm from the array propagated analytically from the data provided by EO-3D, where vx and vz are the x- and z- components of the velocity, respectively. When the emission angle at the tip is ±20°, the angular spread is about ±7° at the mesh; when the emission angle at the tip is ±40°, the angular spread is about ±14° at the mesh.

Three-dimensional Simulations of the Electron Beam Trajectories going through the Mesh

The electron propagation through the mesh was evaluated next. The parameters of the mesh are:

- Thickness: 0.3 mil ≈ 8 μm.
- Holes: 500 holes per inch with 50% fill factor. Assuming square holes, the pitch of the holes is ≈ 50 μm and the hole is ≈ 35 μm × 35 μm.

Figures 6-9 show the simulation of electron beams going toward the mesh with the holes. The domain of the simulation is 100 μm on either side of the mesh. The initial angular spread of the electrons ranged from 0° to 16° near the mesh. The potential at the entrance was calculated based on the electric field between the mesh and the exit of the EO-3D simulation, assuming

parallel plate geometry. The potential at the exit was assumed to have parallel plate geometry between the mesh and photoconductor, which is a good approximation.

Figure 6 shows the mesh, the equipotential curves, and the electron trajectories going through the mesh, which was centered exactly between the FEA and the photoconductor. The potentials at the entrance and the exit of the simulation were both 2.89 kV, and the electron beam was given the energy of 2.89 keV at the entrance. The plot shows that the beam propagated through the mesh, as expected.

To evaluate the effect of not centering the mesh exactly, we performed the following two simulations. Figure 7 shows the mesh, the equipotential curves, and the electron trajectories going through the mesh, which is positioned slightly closer to the FEA than to the photoconductor, 2.5mm versus 3.0 mm. The potential at the entrance was 2.8 kV and the potential at the exit was 2.9 kV. The electron beam entered the entrance with 2.8 keV. The plot shows that the beam propagated through the mesh as expected.

Figure 8 shows the mesh, the equipotential curves and the electron trajectories going through the mesh, which is positioned slightly further from the FEA than to the photoconductor, 3.0mm versus 2.5 mm. The potential at the entrance was 2.9 kV, and the potential at the exit was 2.8 kV. The electron beam entered the entrance with 2.9 keV. The plot shows that the beam propagated through the mesh as expected.

To evaluate the effect of a mesh that is not fabricated to specification, we performed a simulation of the following worst case scenario. Figure 9 shows the mesh, the equipotential curves, and the electron trajectories going through the mesh, which was centered exactly between the FEA and the photoconductor, but where the mesh was twice as thick, 16 μm, and the holes were half as large, 25 μm × 25 μm. The potentials at the entrance and the exit of the simulation were both 2.89 kV, and the electron beam was given the energy of 2.89 keV at the entrance. Again, the plot shows that the beam propagated through the mesh as expected.

The mesh performed the function as expected.

Three-dimensional Simulations of the Electron Beam Propagation from the Mesh to the Photoconductor

The propagation of the electron beam from the mesh to the photoconductor was performed in the last simulation using EO-3D. The mesh was set to 3 kV and the photoconductor was set to 100 V. Electrons had an initial energy of 3 keV and an initial angular spread from 0° to 14°. Figure 10 shows that the electrons with an angular spread of 11° or larger are turned back toward the mesh. These results indicate that electrons which are emitted from the tip within an initial emission angle of ±25° can reach the photoconductor. An electron emission angle from the tip with ±25° is typical. However the spot size formed by a pixel on the photoconductor is very large, about 2.75 mm in diameter. The 2.75 mm spread is obtained by combining the 0.75 mm introduced from the FEA to the mesh and the 2 mm introduced from the mesh to the photoconductor.

Conclusions and Comments

The simulations and calculations suggest that the majority of the electrons emitted from the field emitter tips are expected to reach the photoconductor, except for the percentage that get intercepted at the mesh, for a gate-to-tip voltage of 65 V. However, the electron spot size on the photoconductor produced by a single pixel is very large, about 2.75 mm in diameter, while the pixel size is only about 0.118 mm. This large difference can completely prevent FEXIS from producing images.

If the electron beam spot size on the photoconductor is 2.75 mm and the pitch of the field emitter pixel is also 2.75 mm, then it may be possible to produce very coarse images with resolution of about 2.75 mm.

However, if the electron beam spot size on the photoconductor is 2.75 mm and the pitch of the field emitter pixel is only 0.118 mm, then the charge collected would be small, at the same level as noise. The large spot size wipes out most of the charge on the photoconductor before the sampling beam arrives; this is illustrated in Fig. 11. Each large circle represents the electron beam spot size produced by one pixel. The pitch of the pixel is 1/25 of the diameter of the circle. The dark outlined circle represents the most recent pixel that was turned on. The black area is the portion that has not been previously illuminated by the electron beam. The current density at the edge of the beam is lower than the current density near the center. Figure 11 illustrates that the available current in that portion of the electron beam is very small. In addition, the charge read-out is not clearly associated with a specific spot, because the beam does not have a hard cut-off edge for the region shown in Fig. 11.

We had assumed in the simulation a voltage of 65 V from the gate to the tip of the field-emitter, which was probably on the low side. A larger gate to tip voltage would have led to larger transverse velocity. The larger transverse velocity would not have resulted in a much larger electron beam spot on the photoconductor, because the portion of the beam with larger angular spread would have been turned back to the mesh. However, the larger transverse velocity would have resulted in reduced current to the photoconductor.

The combination of the large electron beam spot size on the photoconduction, and the large gate to emitter voltage would result in readout charge collection in the noise level.

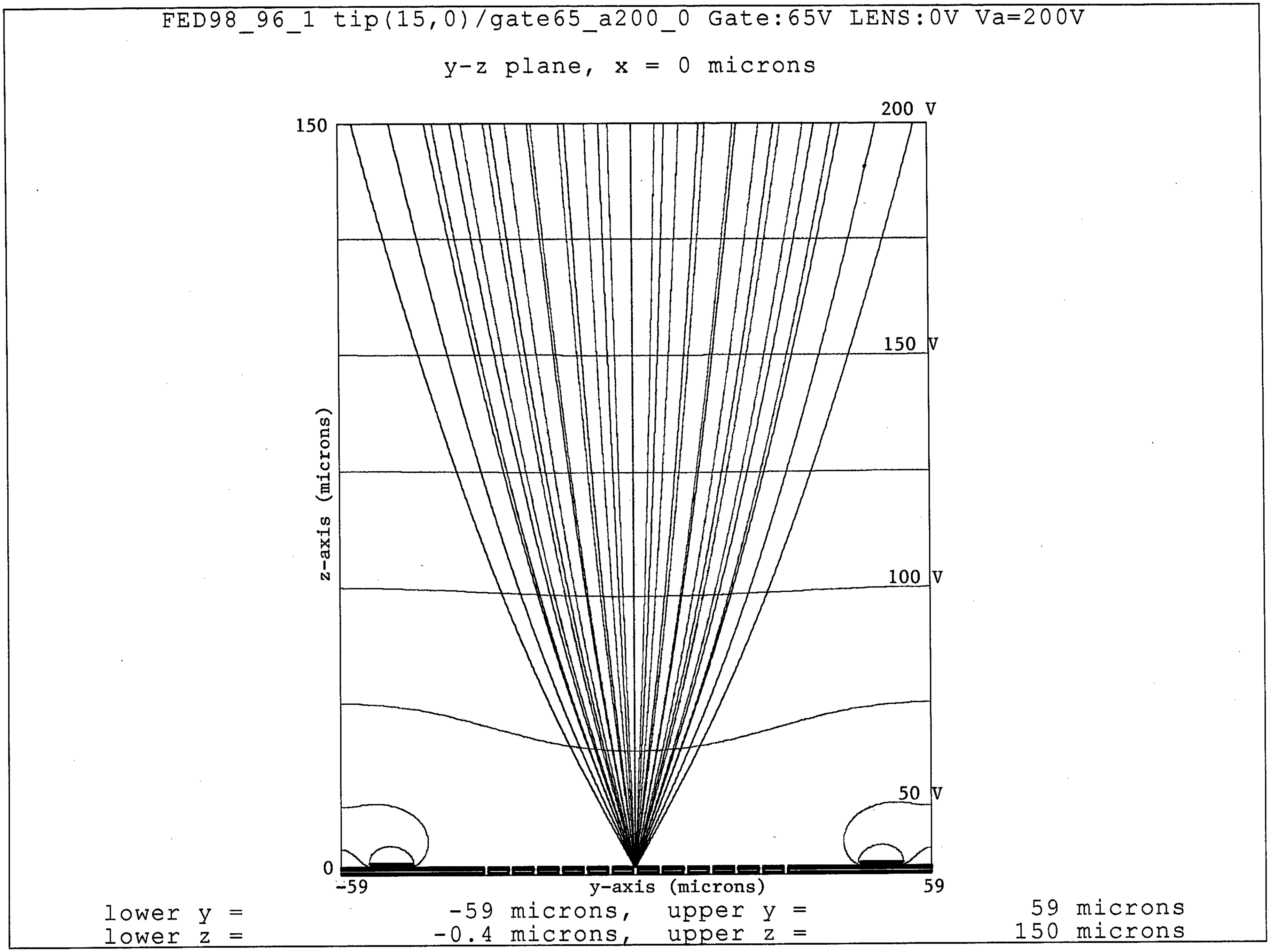

FED98_96_1 tip(15,0)/gate65_a200_0 Gate:65V LENS:0V Va=200V
y-z plane, x = 0 microns
200 V
150 V
100 V
50 V
150
0
z-axis (microns)
-59
59
y-axis (microns)
lower y = -59 microns, upper y = 59 microns
lower z = -0.4 microns, upper z = 150 microns

Figure 1

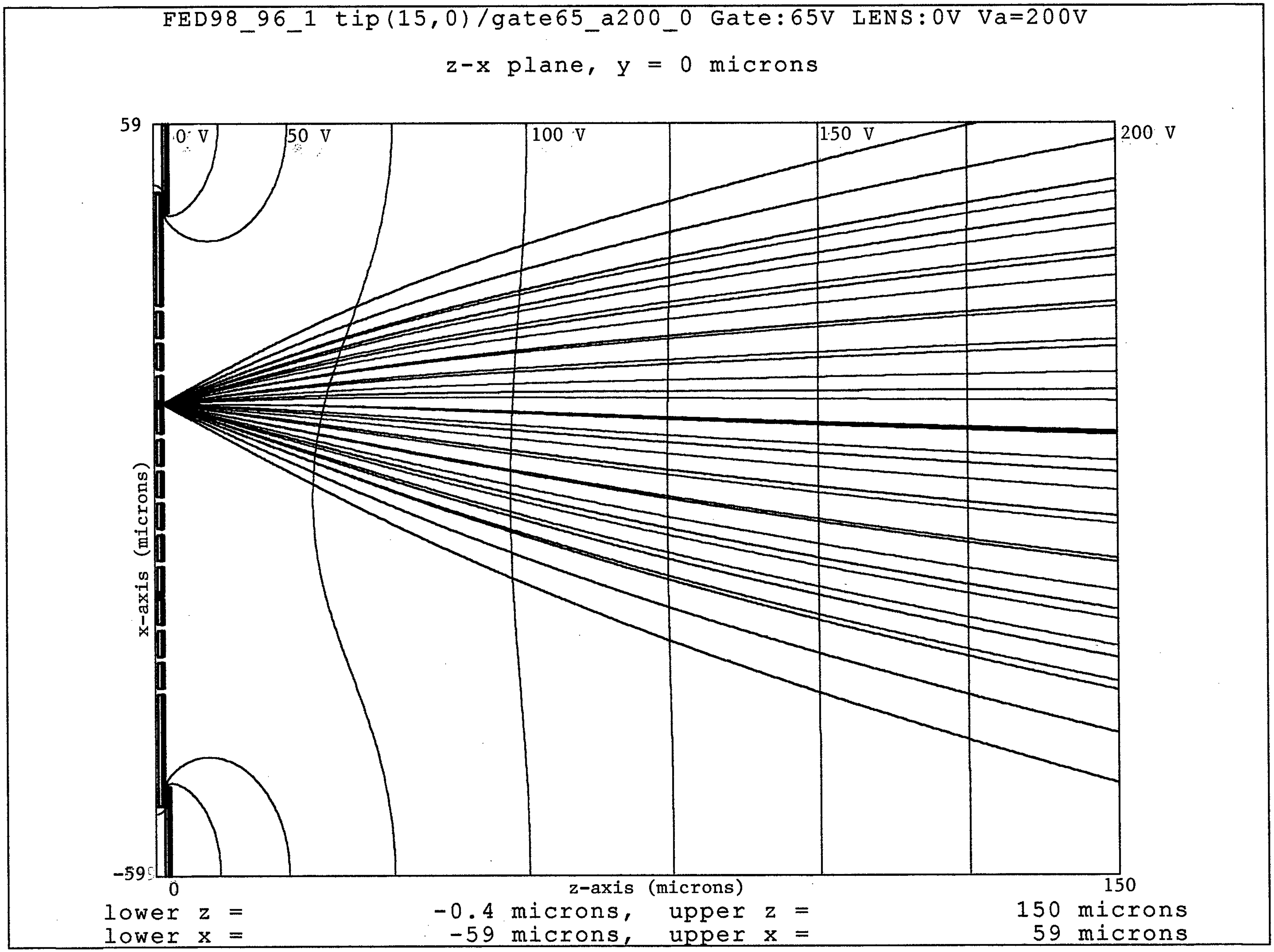
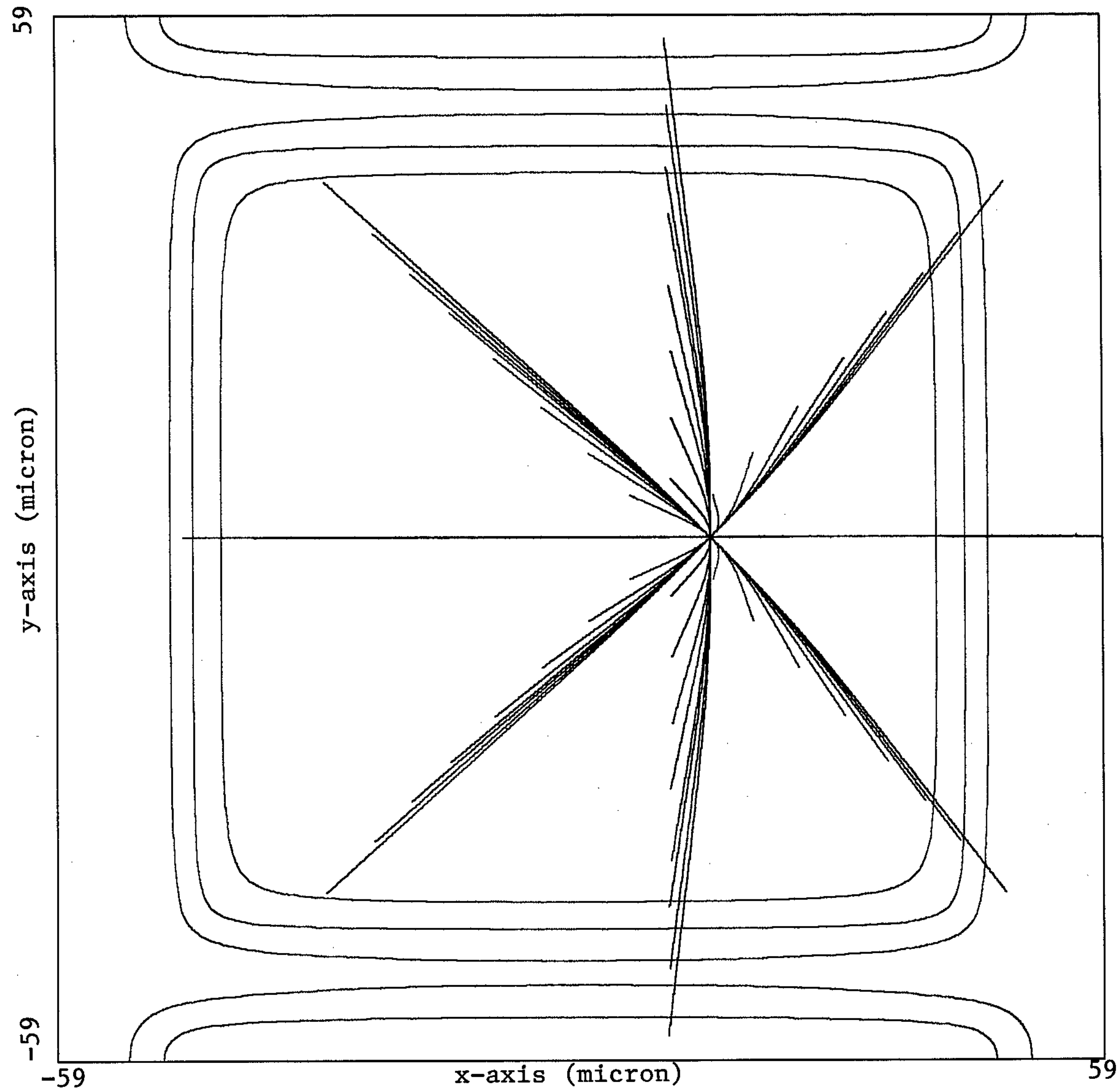

FED98_96_1 tip(15,0)/gate65_a200_0 Gate:65V LENS:0V Va=200V
z-x plane, y = 0 microns
59
-59
0 V
50 V
100 V
150 V
200 V
0
150
x-axis (microns)
z-axis (microns)
lower z = -0.4 microns, upper z = 150 microns
lower x = -59 microns, upper x = 59 microns

Figure 2

FED98_96_1 tip(15,0)/gate65_a200_0 Gate:65V LENS:0V Va=200V

x-y plane, z = 4.95808 microns



lower x = -59 microns, upper x = 59 microns
lower y = -59 microns, upper y = 59 microns

Figure 3

Tip(15,0) V_G=65V, V_L=0V, Anode at 2.75mm V_A=3kV

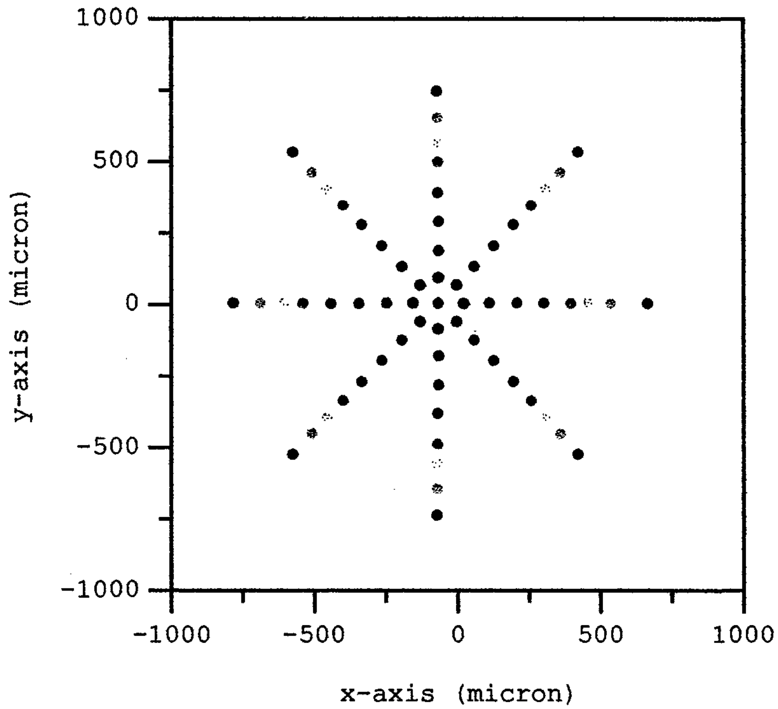


Figure 4

Tip(15,0)(micron), V_G=65V, V_L=0V, Anode at 2.75mm V_A=3.0kV

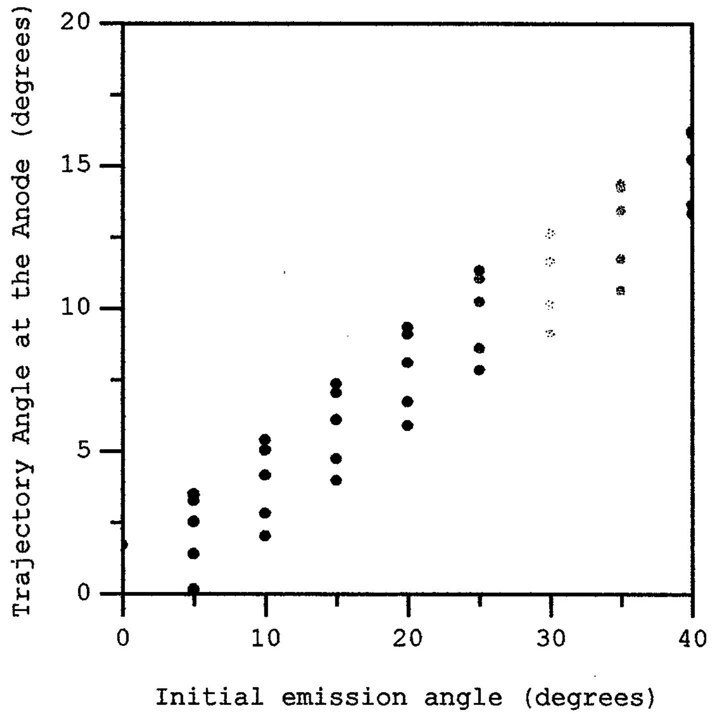


Figure 5

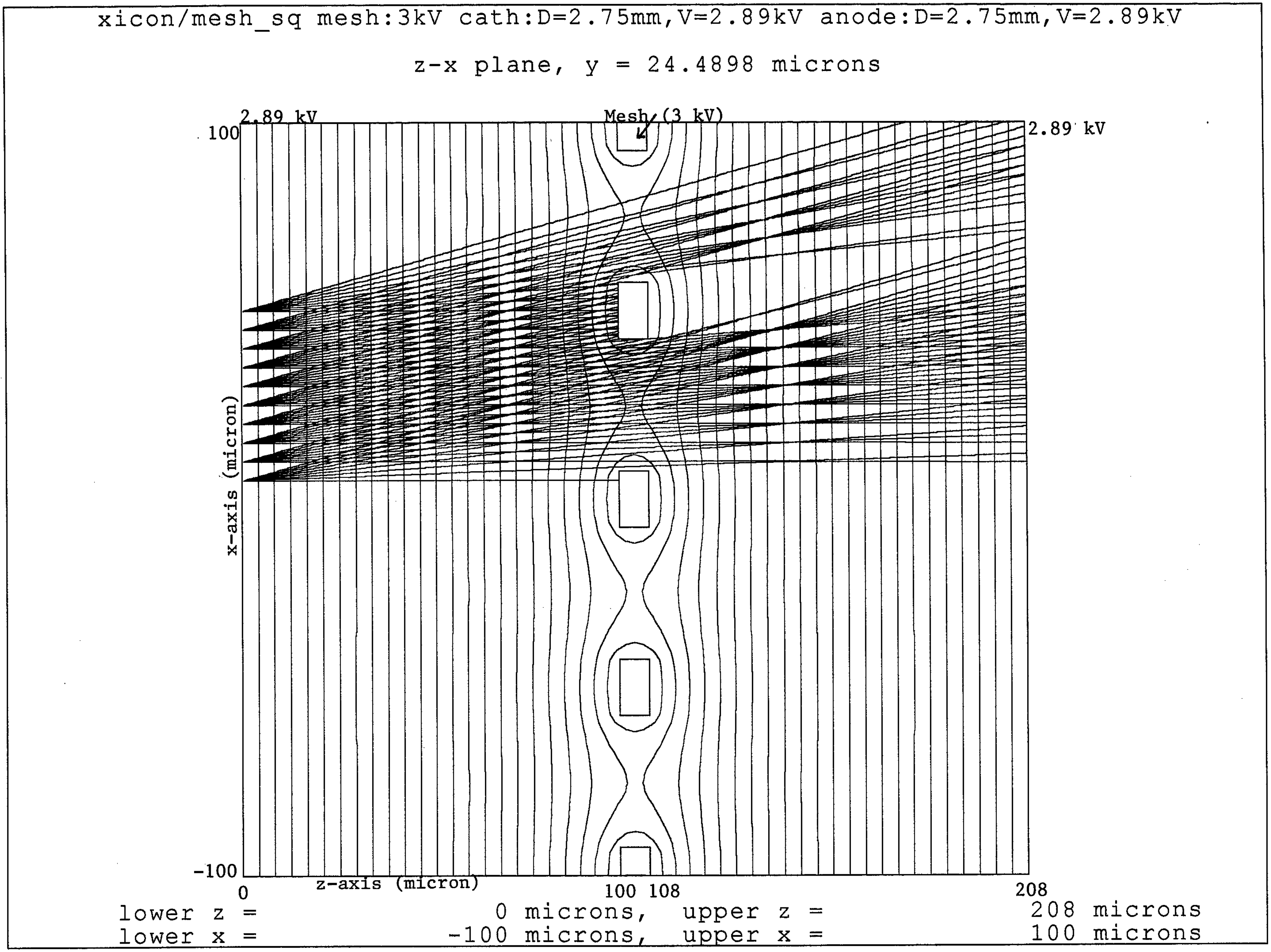
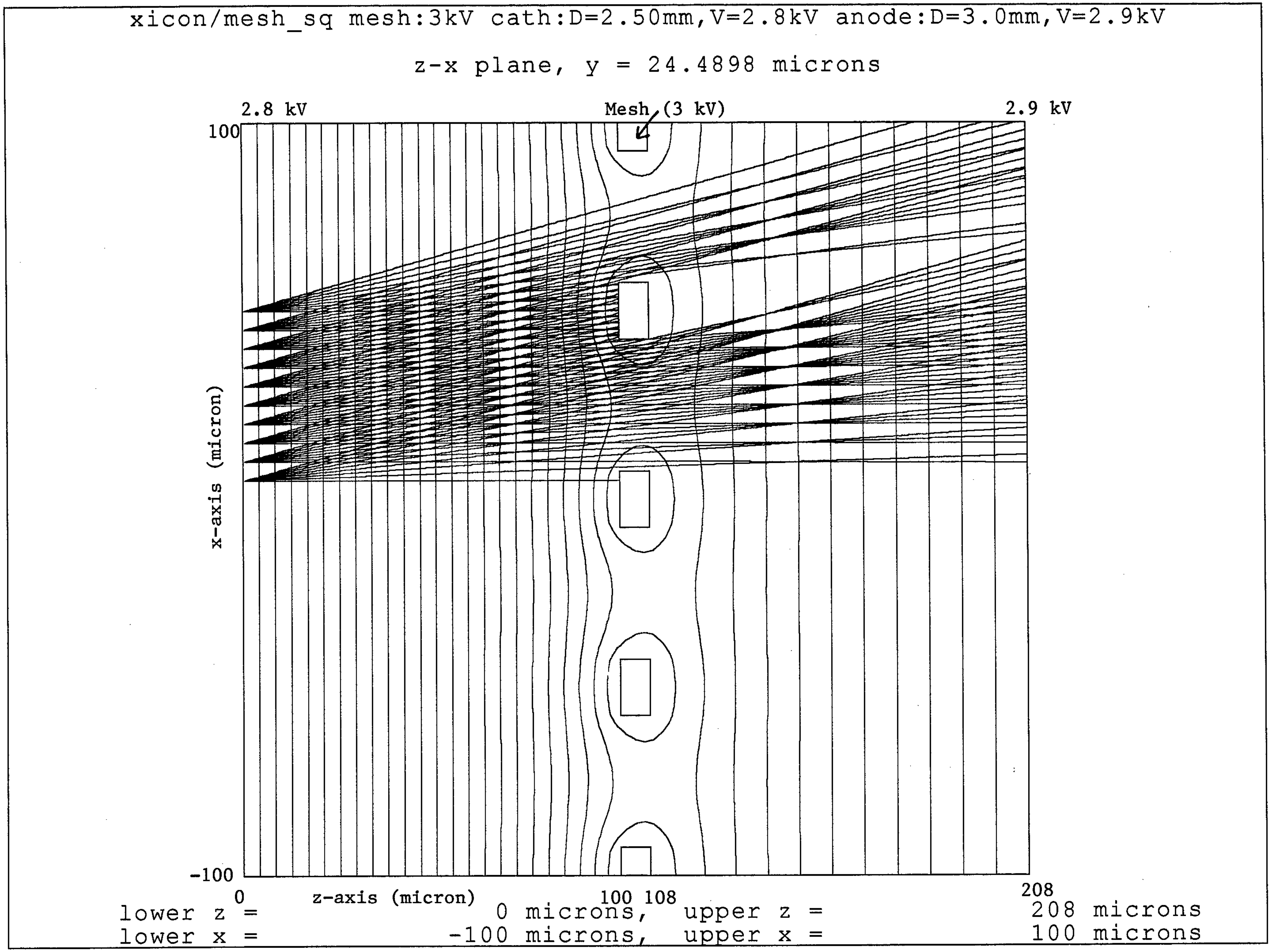

xicon/mesh_sq mesh:3kV cath:D=2.75mm,V=2.89kV anode:D=2.75mm,V=2.89kV
z-x plane, y = 24.4898 microns
2.89 kV
Mesh (3 kV)
2.89 kV
100
-100
x-axis (micron)
0
z-axis (micron)
100 108
208
lower z = 0 microns, upper z = 208 microns
lower x = -100 microns, upper x = 100 microns

Figure 6



xicon/mesh_sq mesh:3kV cath:D=2.50mm,V=2.8kV anode:D=3.0mm,V=2.9kV
z-x plane, y = 24.4898 microns
2.8 kV
Mesh (3 kV)
2.9 kV
100
-100
x-axis (micron)
0
z-axis (micron)
100 108
208
lower z = 0 microns, upper z = 208 microns
lower x = -100 microns, upper x = 100 microns

Figure 7

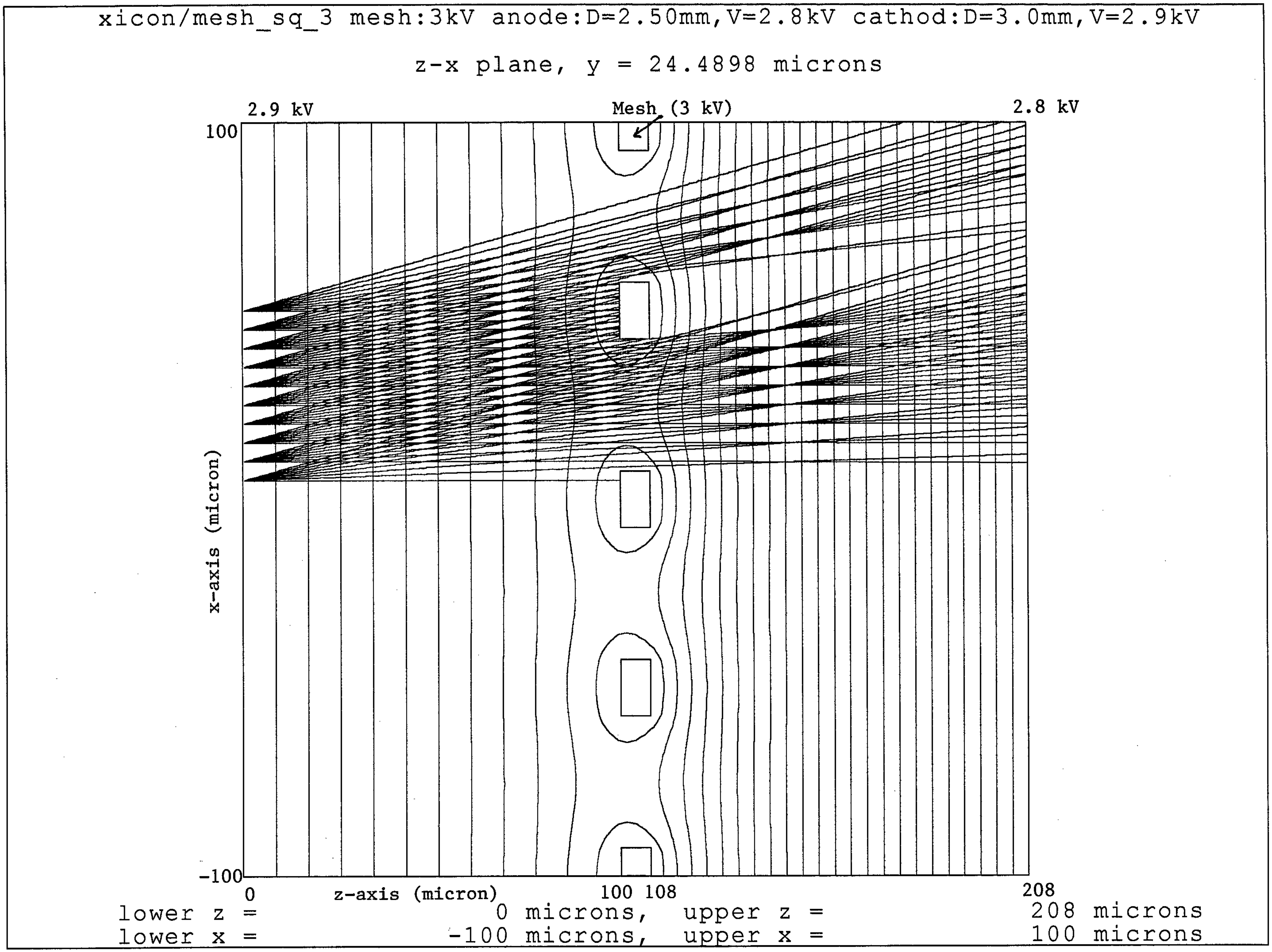

xicon/mesh_sq_3 mesh:3kV anode:D=2.50mm,V=2.8kV cathod:D=3.0mm,V=2.9kV
z-x plane, y = 24.4898 microns
2.9 kV
Mesh (3 kV)
2.8 kV
100
-100
x-axis (micron)
0
z-axis (micron)
100 108
208
lower z = 0 microns, upper z = 208 microns
lower x = -100 microns, upper x = 100 microns

Figure 8

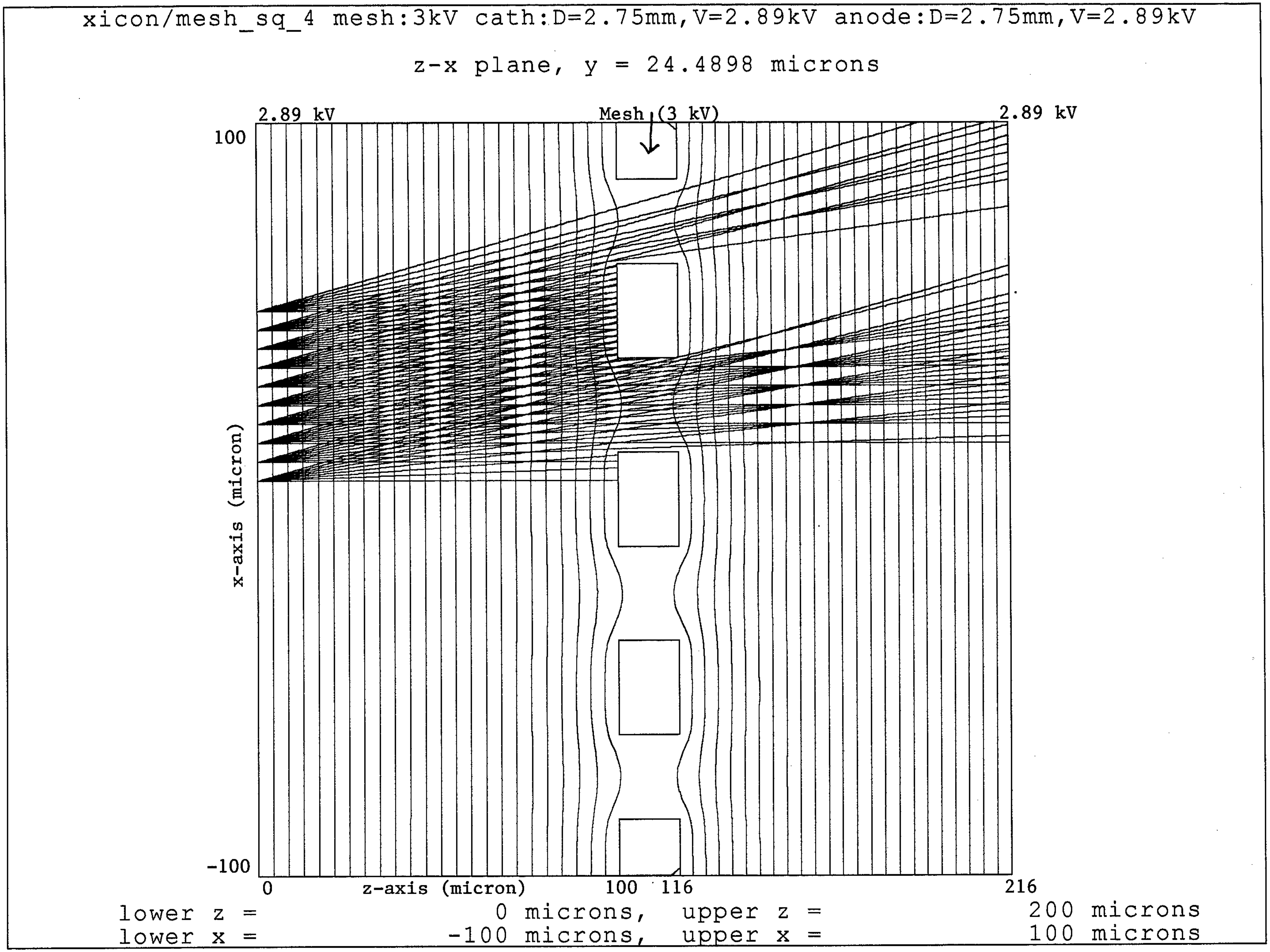
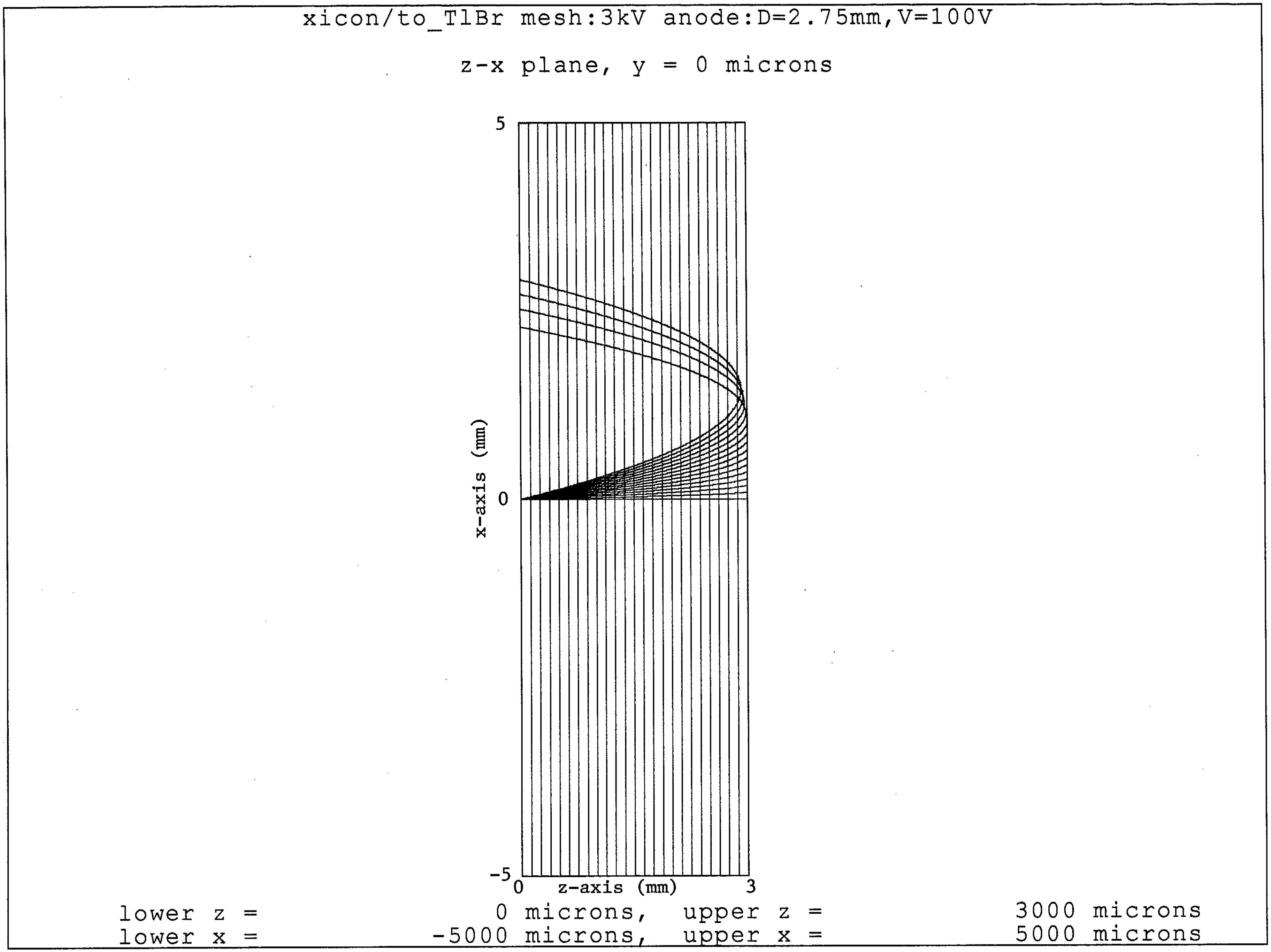

xicon/mesh_sq_4 mesh:3kV cath:D=2.75mm,V=2.89kV anode:D=2.75mm,V=2.89kV
z-x plane, y = 24.4898 microns
2.89 kV
Mesh (3 kV)
2.89 kV
100
-100
x-axis (micron)
0
z-axis (micron)
100
116
216
lower z = 0 microns, upper z = 200 microns
lower x = -100 microns, upper x = 100 microns

Figure 9



xicon/to_TlBr mesh:3kV anode:D=2.75mm,V=100V
z-x plane, y = 0 microns
5
0
-5
x-axis (mm)
0
z-axis (mm)
3
lower z = 0 microns, upper z = 3000 microns
lower x = -5000 microns, upper x = 5000 microns

Figure 10

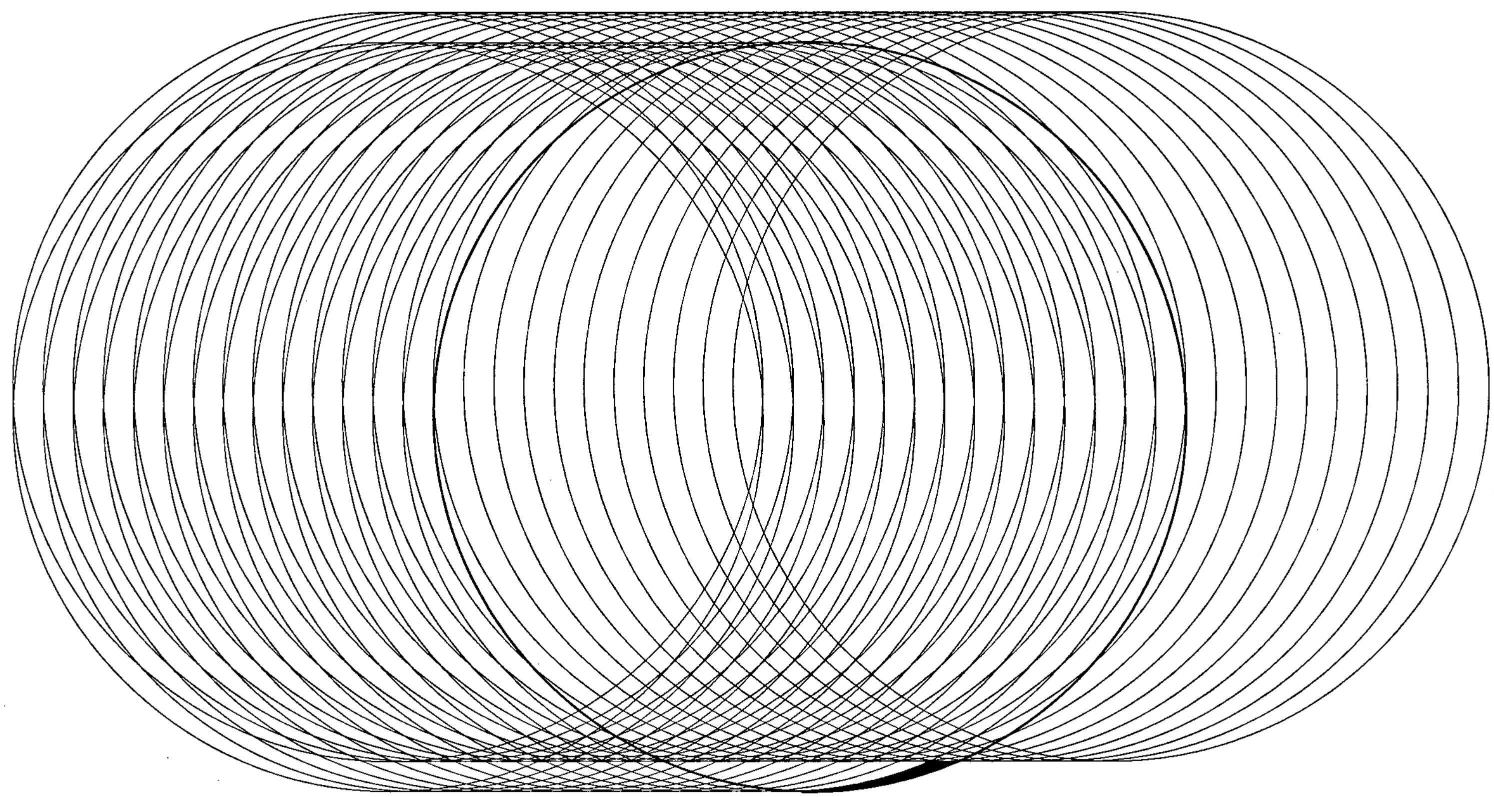


Fig. 11

Xicon_1.cdr